Supernova and low energy neutrinos

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Project X Physics Study
June 2012

What does this have to do with Project X?

1. **An underground large detector in combination with a beam will have excellent SN capabilities**

2. **A source of low energy (few to 100 MeV) neutrinos will enable measurement of supernova-relevant neutrino-nucleus cross-sections**
   (good for other things too...)

Part I:

Neutrinos from core-collapse supernovae

What can be learned

Example: mass hierarchy

Supernova neutrino detection

Summary of current and near future detectors

Future detection

Extragalactic neutrinos

Part II:

Low energy neutrino-nucleus cross-sections

What's known

Potential for measurments with a DAR source

(and more physics w/ low energy neutrinos...)

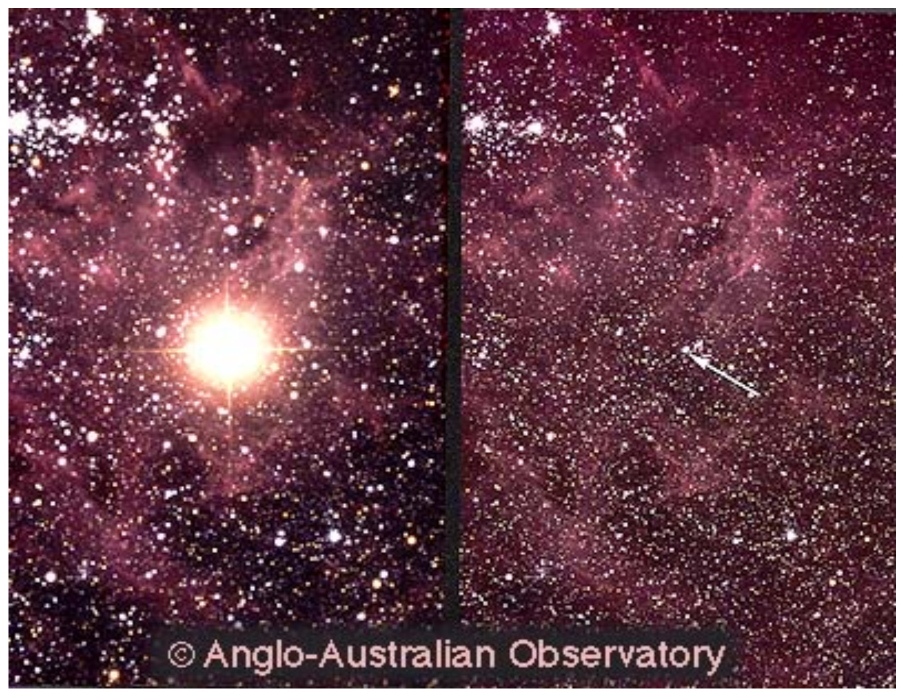
Neutrinos from core collapse

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of *all flavors* with ~tens-of-MeV energies

(Energy *can* escape via ν's)

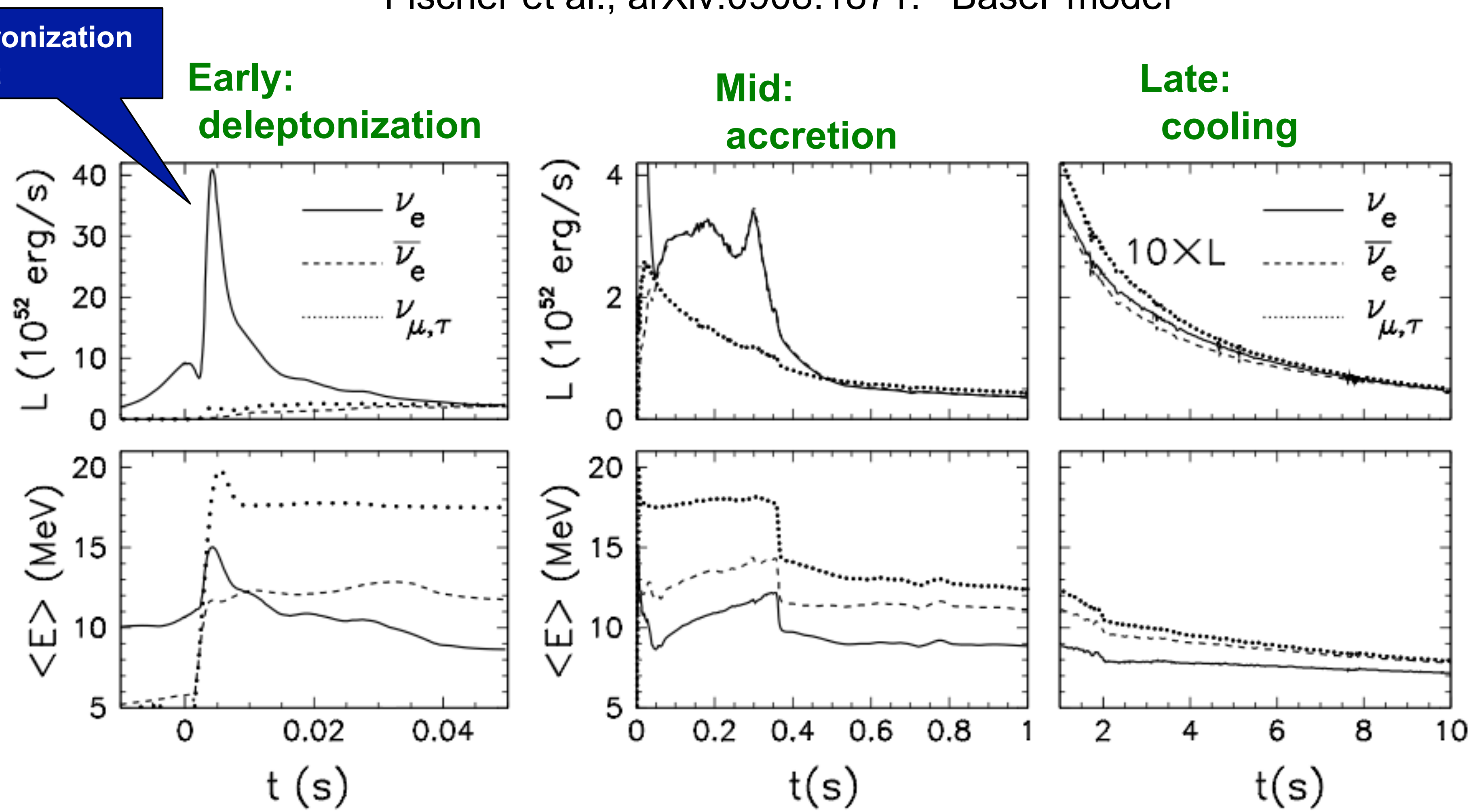
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Expected neutrino luminosity and average energy vs time

Fischer et al., arXiv:0908.1871: ‘Basel’ model



Generic feature:

(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

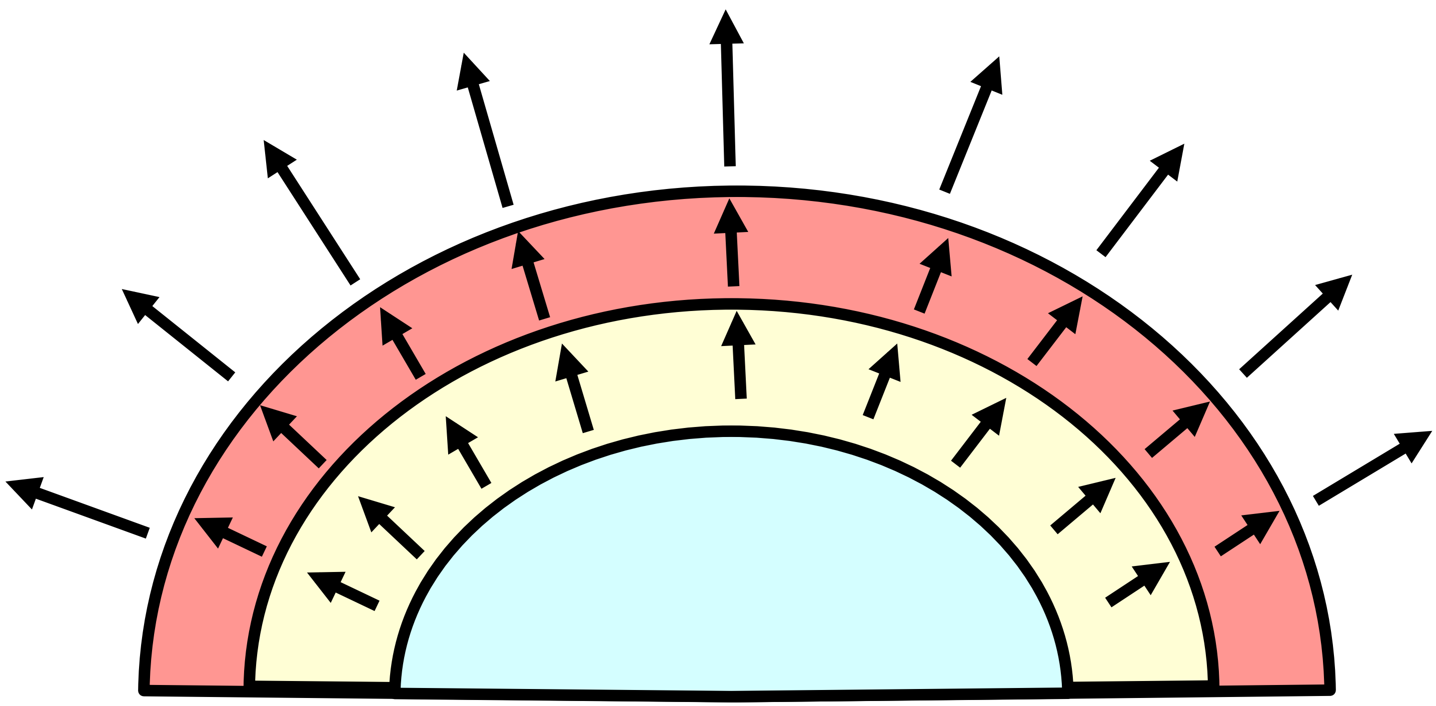
Nominal expected flavor-energy hierarchy

Fewer interactions w/ proto-nstar
⇒ deeper ν-sphere
⇒ hotter ν's

$\langle E_{\nu_e} \rangle \sim 12$ MeV

$\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV

$\langle E_{\overset{(-)}{\nu}_{\mu,\tau}} \rangle \sim 18$ MeV



May or may not be robust (neutrinos which decouple deeper may lose more energy)

Raffelt, astro-ph/0105250; Keil, Raffelt & Janka astro-ph/0208035

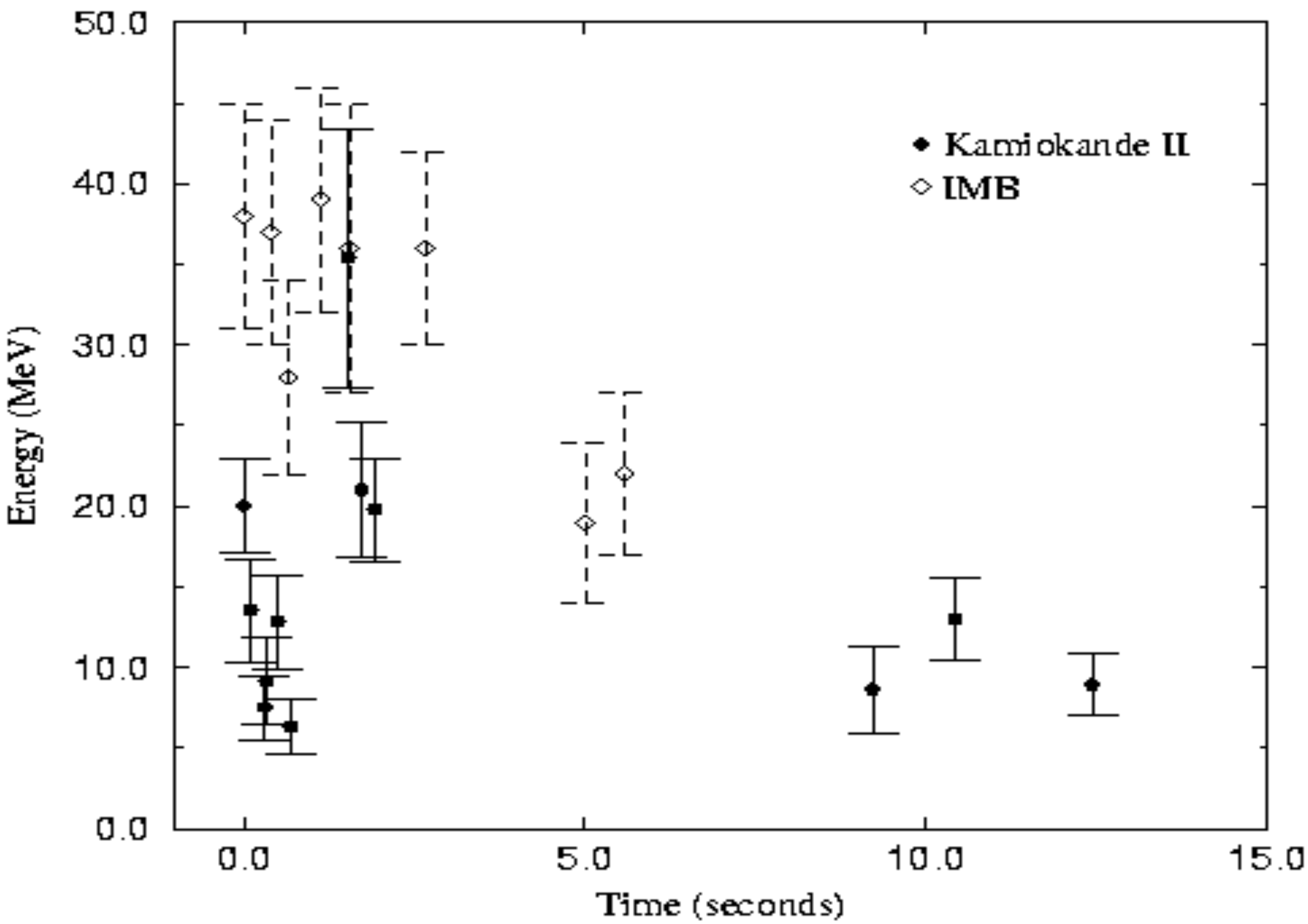
Supernova 1987A
in the Large Magellanic Cloud (55 kpc away)

SN1987A in LMC

at 55 kpc
ν's seen ~2.5 hours before first light

Water Cherenkov: IMB E_{th}~ 29 MeV, 6 kton 8 events
Kam II E_{th}~ 8.5 MeV, 2.14 kton 11 events

Liquid Scintillator: Baksan E_{th}~ 10 MeV, 130 ton 3-5 events
Mont Blanc E_{th}~ 7 MeV, 90 ton 5 events??

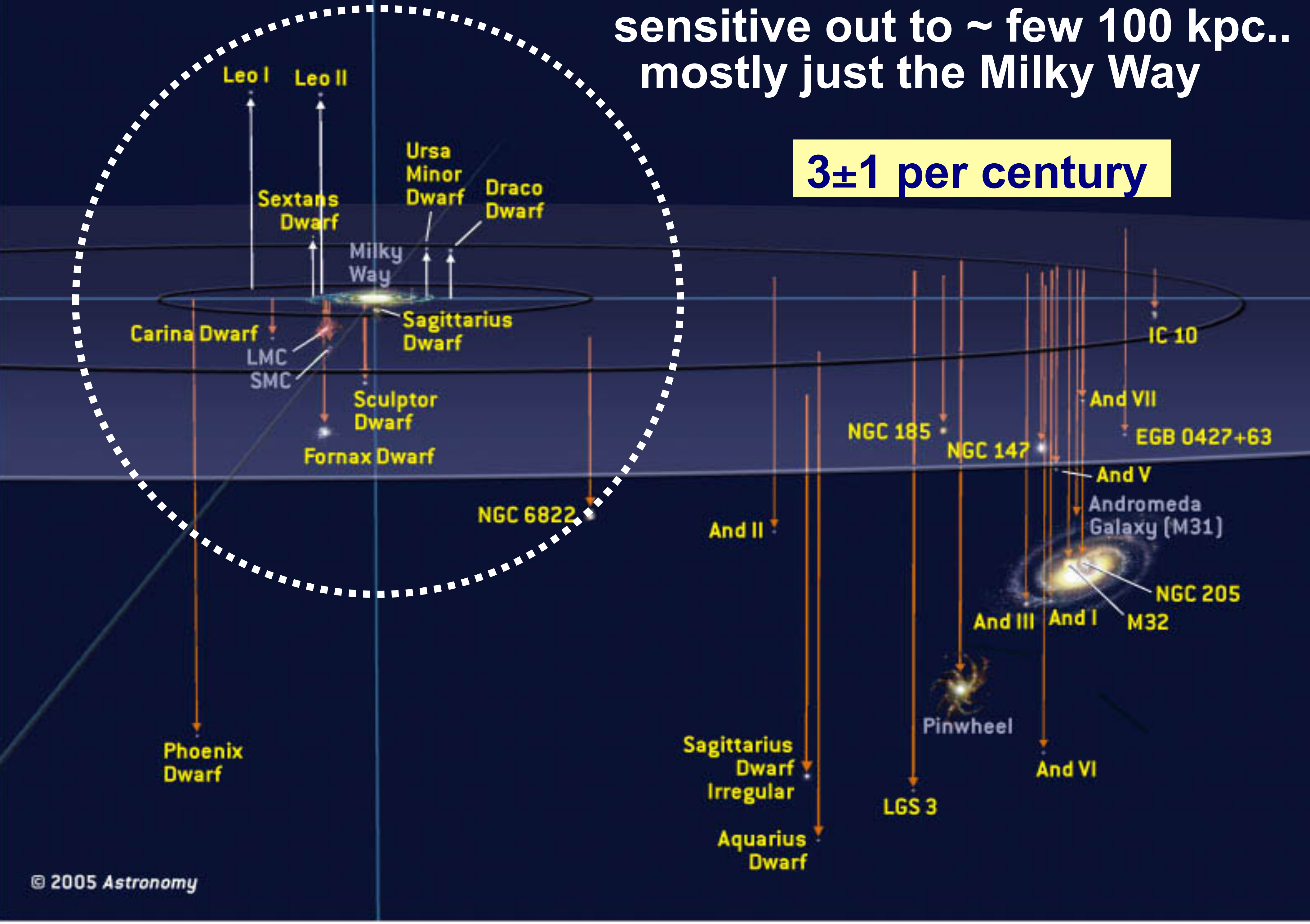


$\bar{\nu}_e$

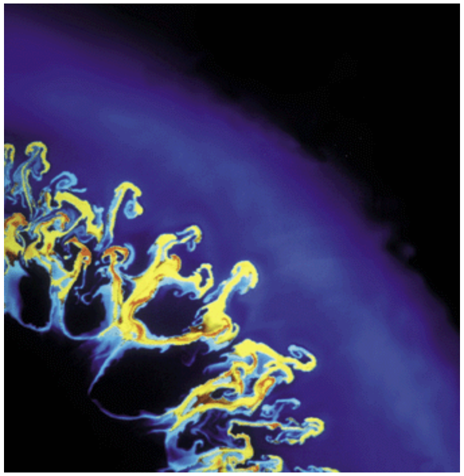
Confirmed baseline model... but still many questions

Current best neutrino detectors sensitive out to ~ few 100 kpc.. mostly just the Milky Way

3±1 per century



What We Can Learn

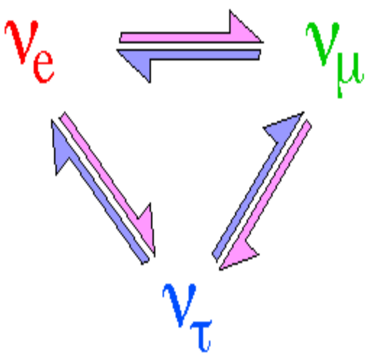


CORE COLLAPSE PHYSICS

- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS



- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
  (' θ_{13} the lucky and patient way')
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

How can we learn about unknown neutrino oscillation parameters from a core collapse signal?

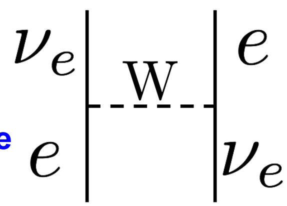
In the proto-neutron star the neutrino density is so high that *neutrino-neutrino interactions* matter

$$\psi_{\nu,i} = \begin{bmatrix} \text{amplitude to be } \nu_{\mathrm{e}} \\ \text{amplitude to be } \nu_{\mu,\tau} \end{bmatrix}$$

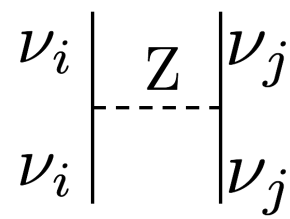
From G. Fuller

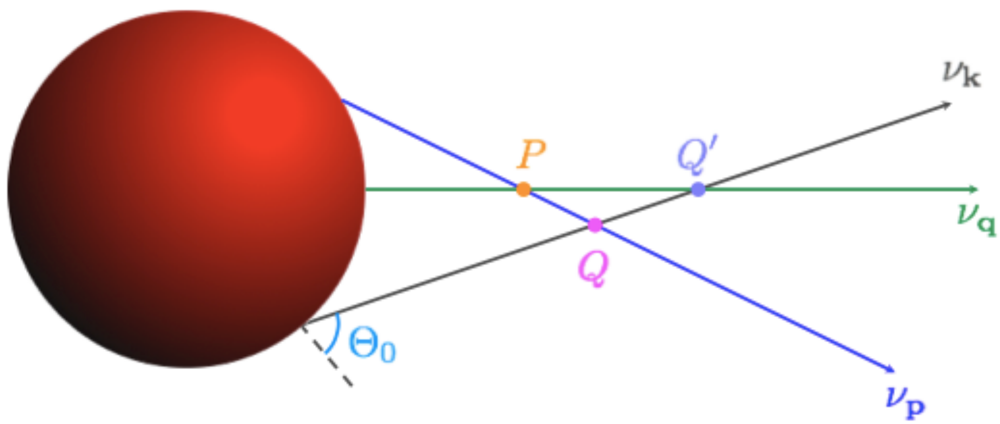
$$i\,\frac{\partial}{\partial t}\psi_{\nu,i} = \left(\mathcal{H}_{\mathrm{vac},i} + \mathcal{H}_{\mathrm{e},i} + \mathcal{H}_{\nu\nu,i}\right)\psi_{\nu,i}$$

neutrino-electron charged current forward exchange scattering



neutrino-neutrino neutral current forward scattering





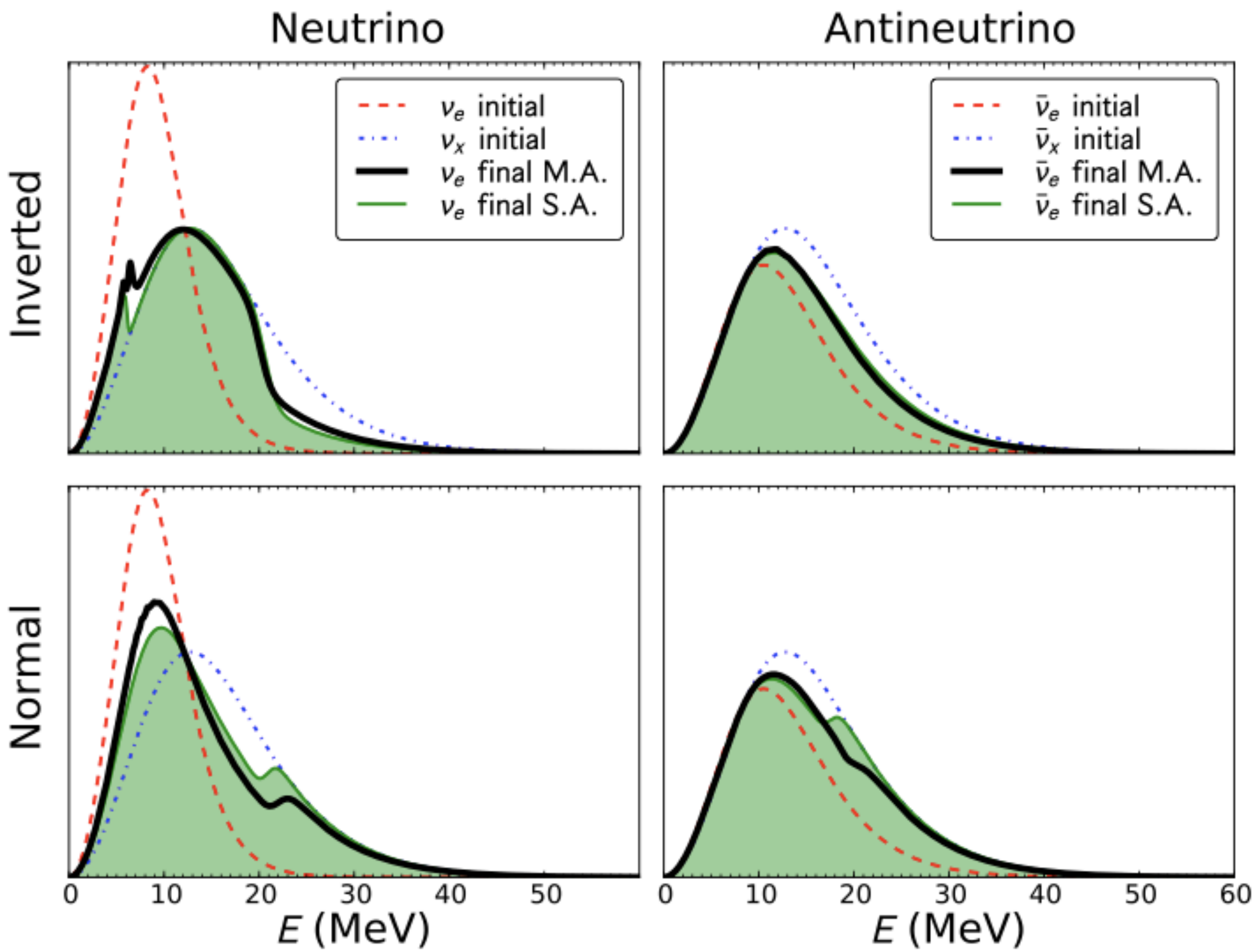
Anisotropic, nonlinear quantum coupling of all neutrino flavor evolution histories:

"collective effects"

Must solve many *millions* of coupled, nonlinear partial differential equations!!

"The physics is addictive" -- G. Raffelt

Example of collective effects: Duan & Friedland, arXiv:1006.2359



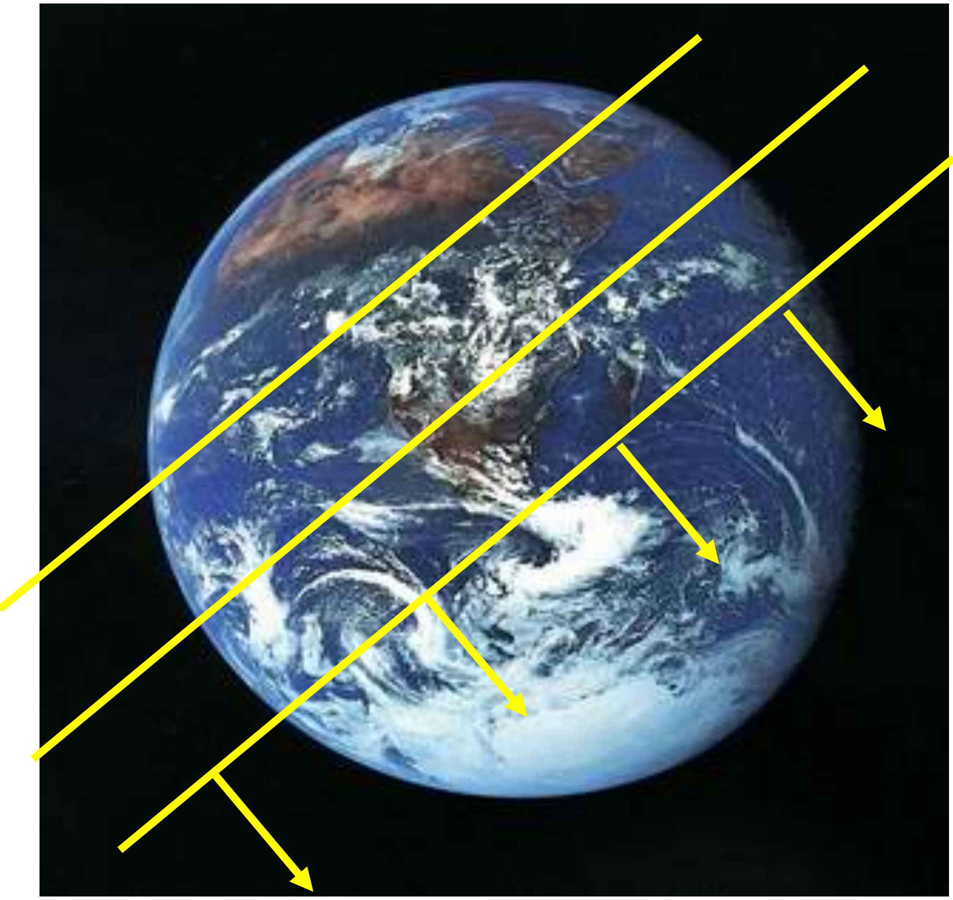
Distinctive spectral swap features depend on neutrino mass hierarchy, **for neutrinos vs antineutrinos**

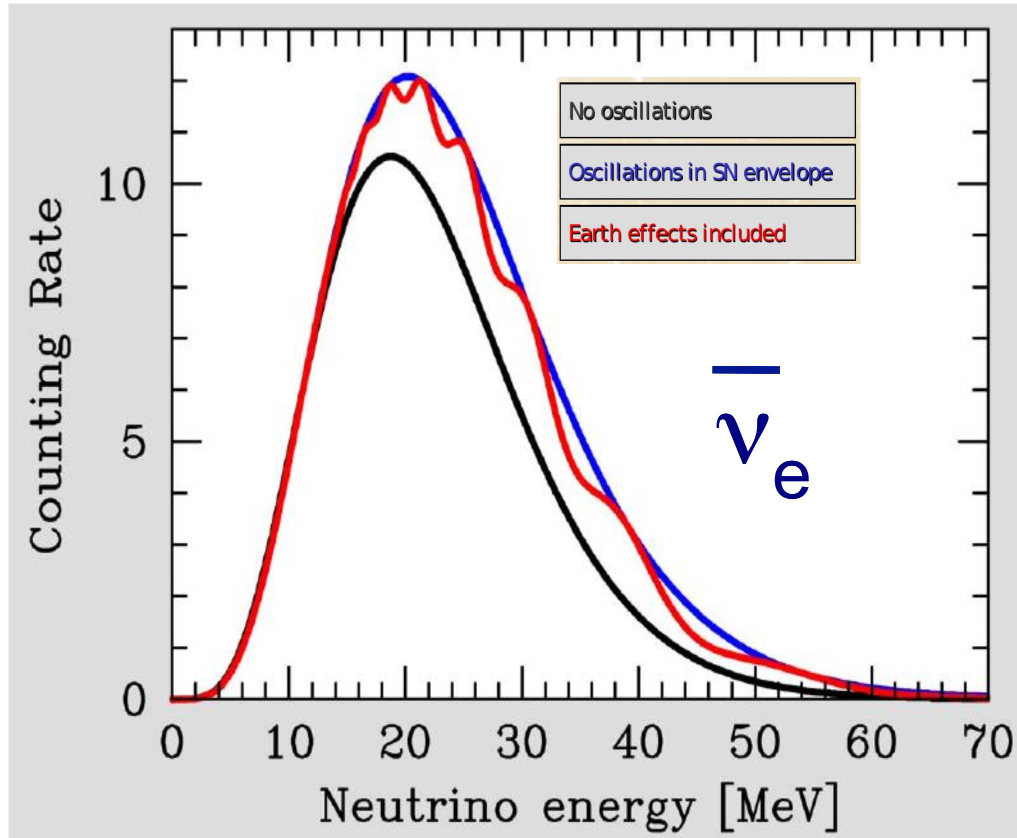
Experimentally, can we tell the difference?

Another possibility:

Flavor transformation *in the Earth* can give a handle on oscillation parameters (less SN-dependence)

Kachelreiss, Raffelt et al.





Compare fluxes of different flavors a different locations; or, look for spectral distortions in a single detector

What do we want in a SN ν detector?

- Need ~ 1kton for ~ few 100 interactions for burst at the Galactic center (8.5 kpc away)

- Must have bg rate << rate in ~10 sec burst (typically easy for underground detectors, even thinkable at the surface)

Also want:
- Timing
- Energy resolution
- Pointing
- Flavor sensitivity

Require NC sensitivity for $\nu_{\mu,\tau}$, since SN ν energies below CC threshold

Sensitivity to different flavors *and ability to tag interactions* is key!

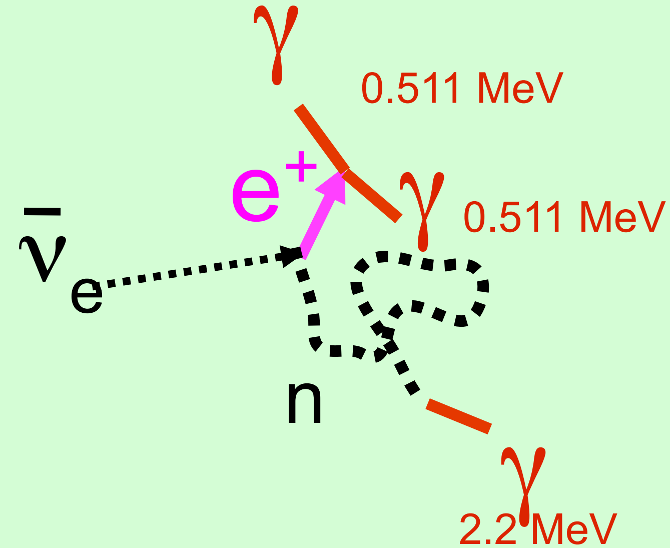
ν_e vs $\bar{\nu}_e$ vs ν_x

Neutrino interactions in the few-tens-of-MeV range

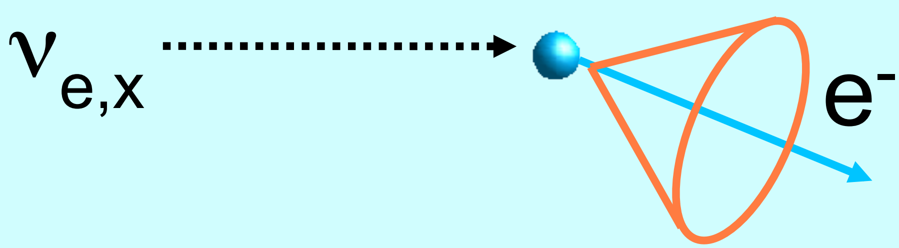
Inverse Beta Decay (CC)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

In any detector with lots of free protons (e.g. water, scint) this dominates



Elastic scattering on atomic electrons



$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

(useful for pointing)

CC and NC interactions on nuclei

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$

$$\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1) + e^+$$

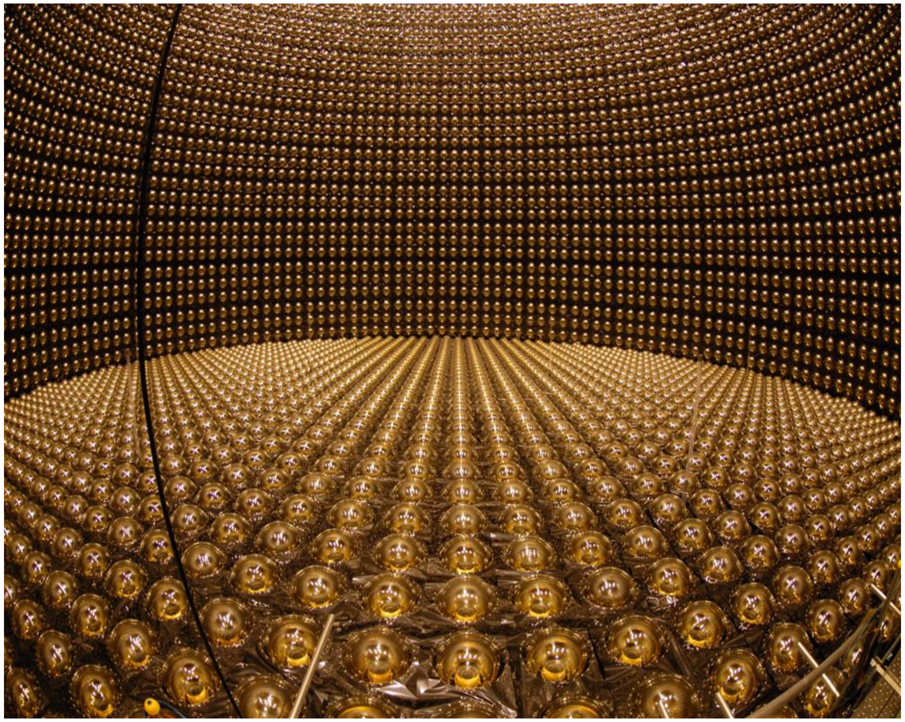
$$\nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x$$

$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

$$\hookrightarrow (A,Z) + \gamma$$

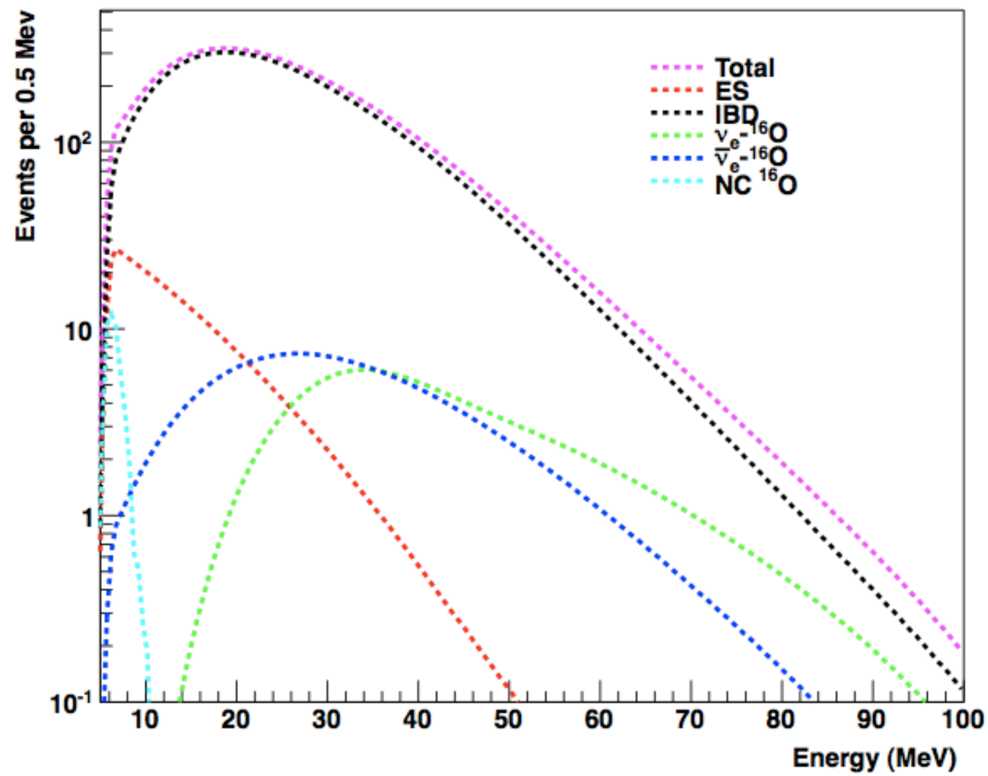
+ NC coherent scattering

Water Cherenkov detectors



- few 100 events/kton

- typical energy threshold
  ~ several MeV makes
  2.2 MeV neutron tag difficult
  (unless Gd added)

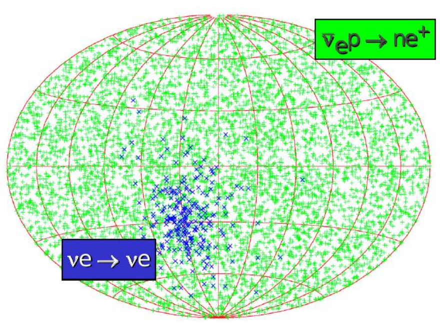


100 kt @ 10 kpc

Inverse Beta Decay (CC) dominates

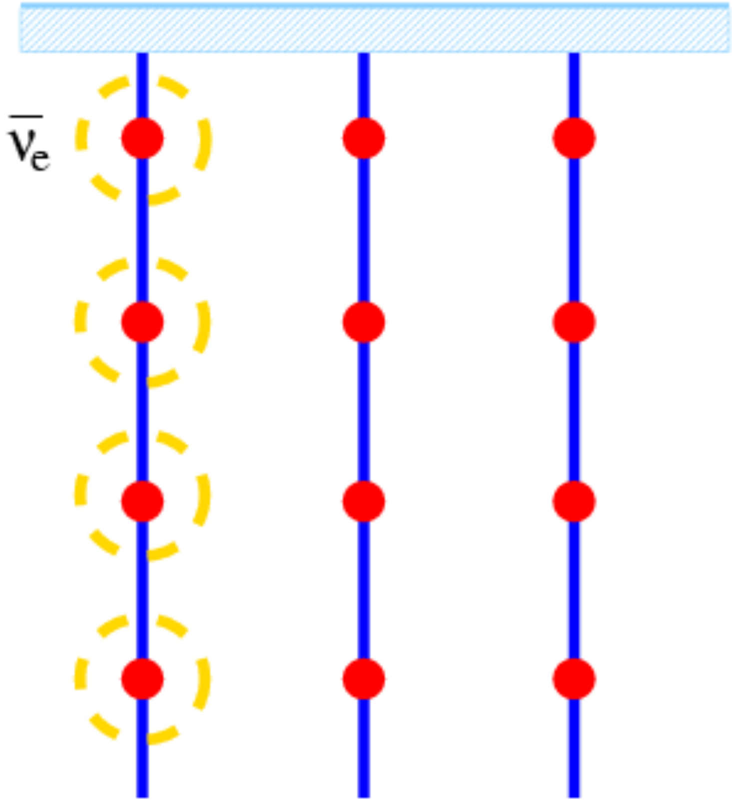
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

E_{thr}=1.8 MeV



Some pointing from ES

Long string water Cherenkov detectors

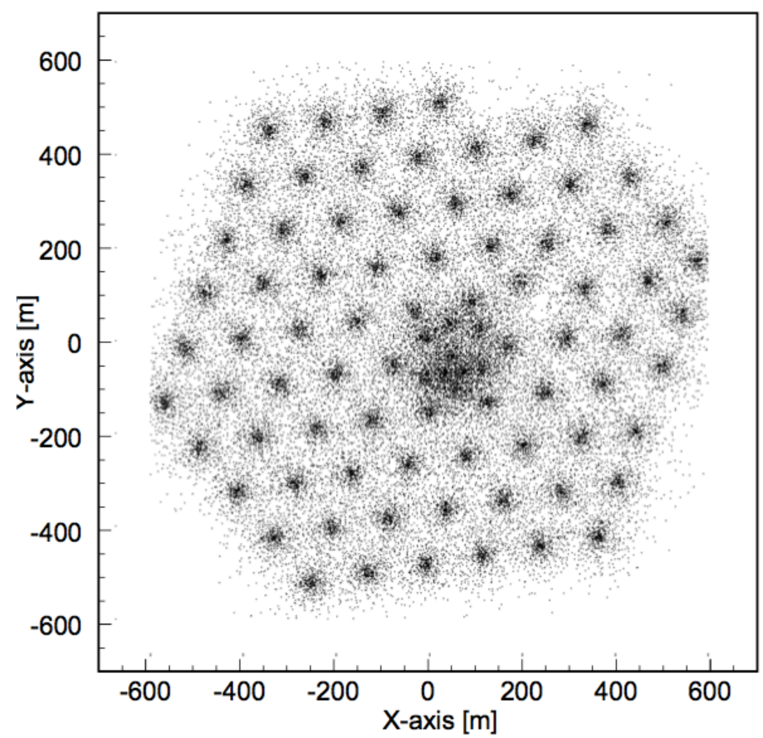


~kilometer long strings of PMTs in very clear water or ice

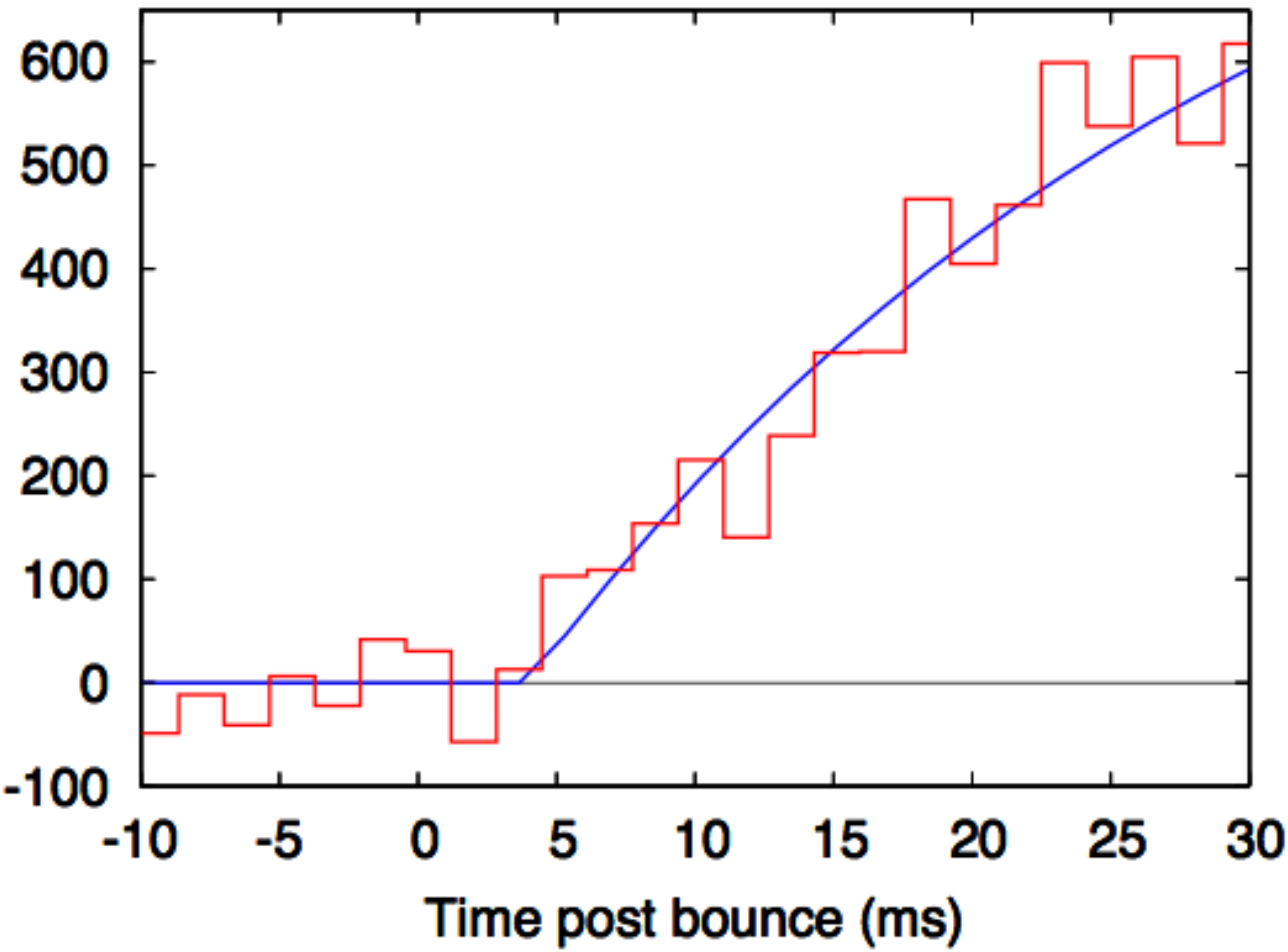
Nominally multi-GeV energy threshold... but, may see burst of low energy $\overline{\nu}_e$'s as *coincident increase in single PMT count rates* (M_{eff}~ 0.7 kton/PMT)

cannot tag flavor, or other interaction info, but gives overall rate and time structure

IceCube at the South Pole, Antares

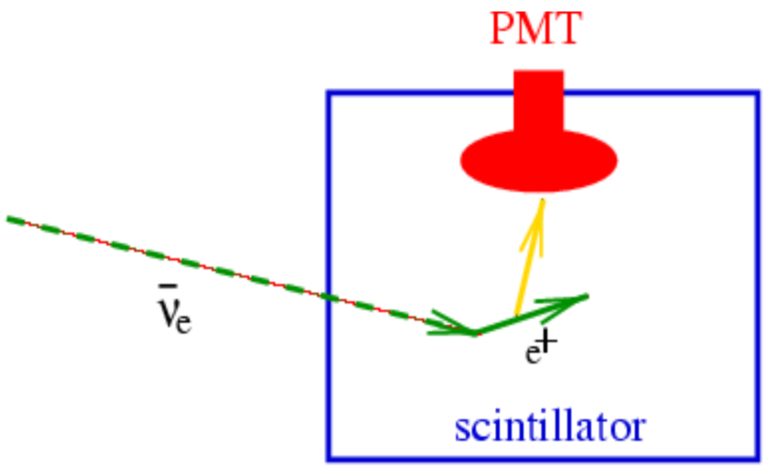


Halzen & Raffelt, arXiv:0908.2317



Few ~ms timing may be possible @ 10 kpc w/IceCube

Scintillation detectors

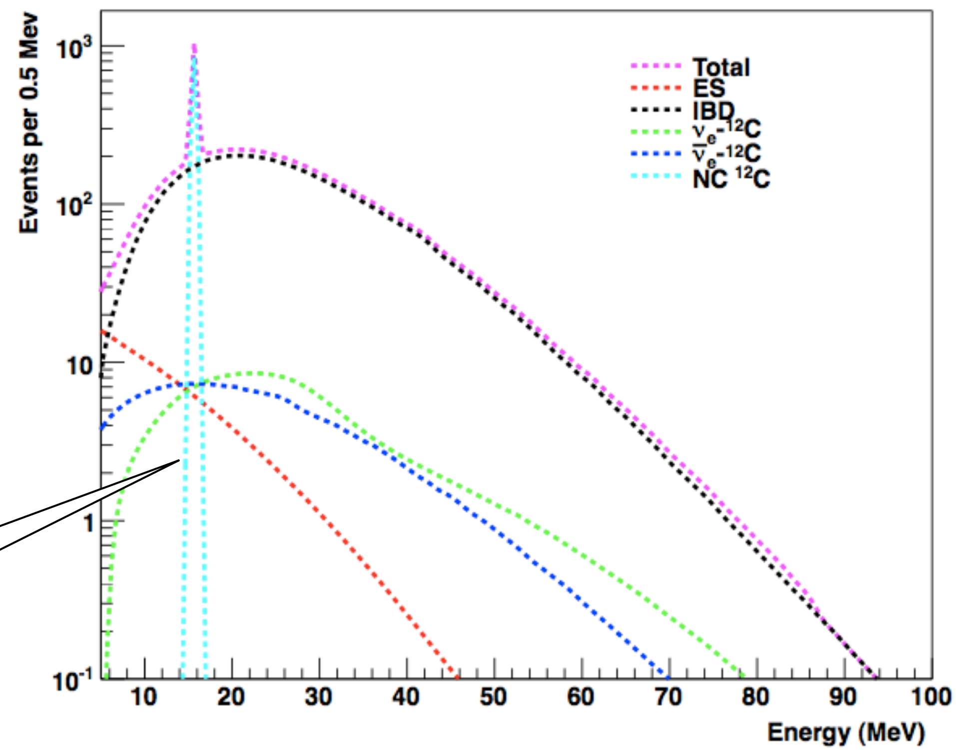


Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

LVD, KamLAND, Borexino, SNO+, (MiniBooNE)
+Double Chooz, Daya Bay and RENO

- few 100 events/kton
- low threshold, good neutron tagging possible
- little pointing capability (light is ~isotropic)
- coherent elastic scattering on on protons for ν spectral info

NC tag from 15 MeV deexcitation γ
(no ν spectral info)



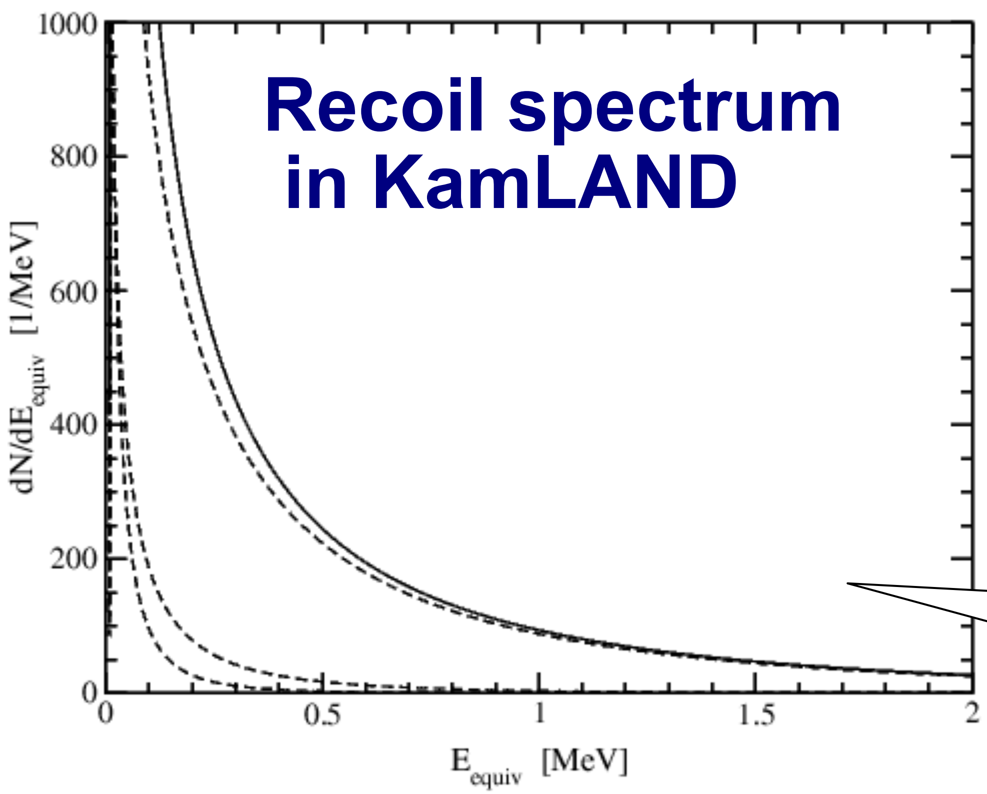
50 kt @ 10 kpc

NC neutrino-proton elastic scattering

$$\nu_x + p \longrightarrow \nu_x + p$$

J. Beacom et al., hep-ph/0205220

Recoil energy small, but visible in scintillator (accounting for 'quenching')



Expect ~few 100 events/kton for 8.5 kpc SN

Neutrino spectral information from recoil energies

Liquid argon time projection chambers

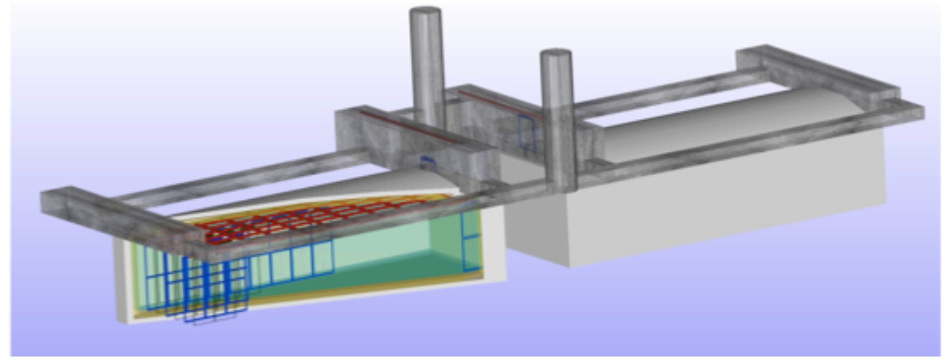
e.g. Icarus, LBNE LAr

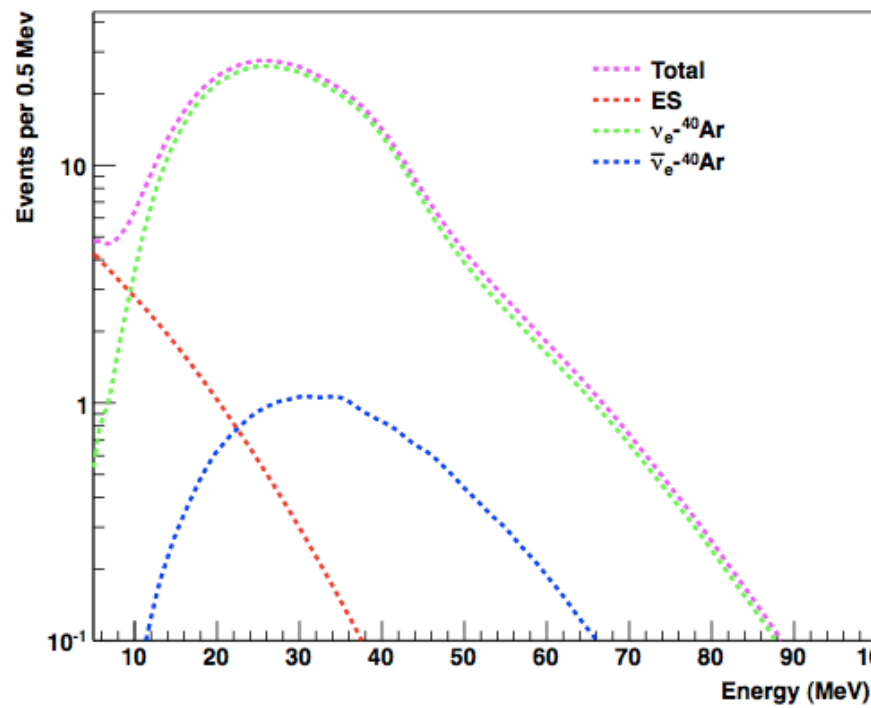
CC $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$

NC $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$

ES $\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$





17 kt @ 10 kpc

- **Tag modes with gamma spectrum (or lack thereof)**
- **Excellent electron neutrino sensitivity**

HALO at SNOLab

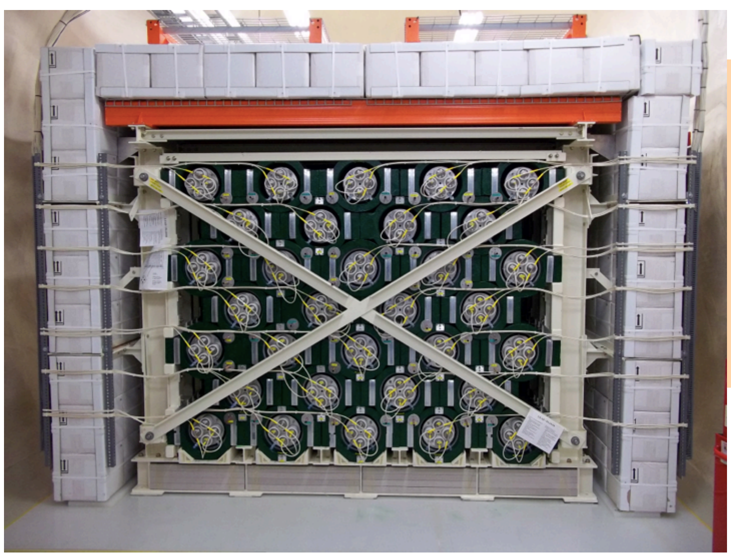
$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^-$ CC

1n, 2n emission

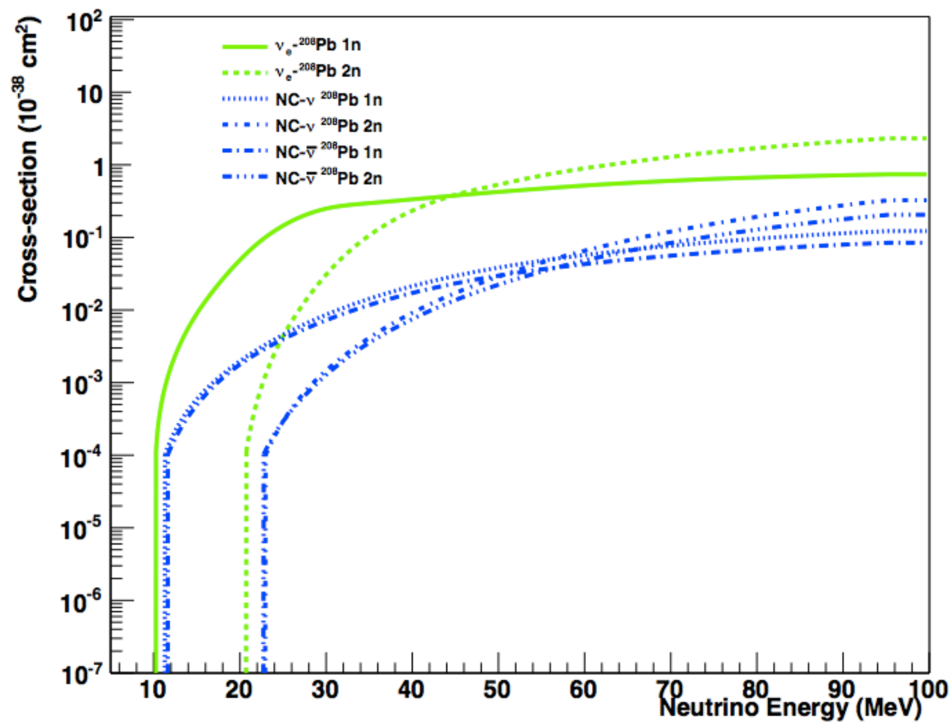
$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x$ NC

1n, 2n, γ emission

Relative 1n/2n rates sharply dependent on ν energy
$\Rightarrow$ spectral sensitivity
(oscillation sensitivity)



HALO operational as of May 2012!

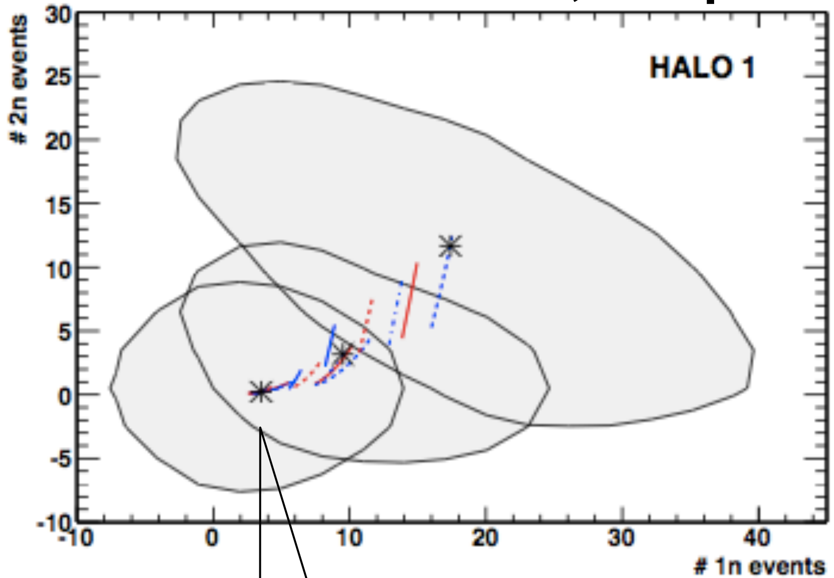


SNO ^{3}He counters + 79 tons of Pb: ~1-40 events @ 10 kpc

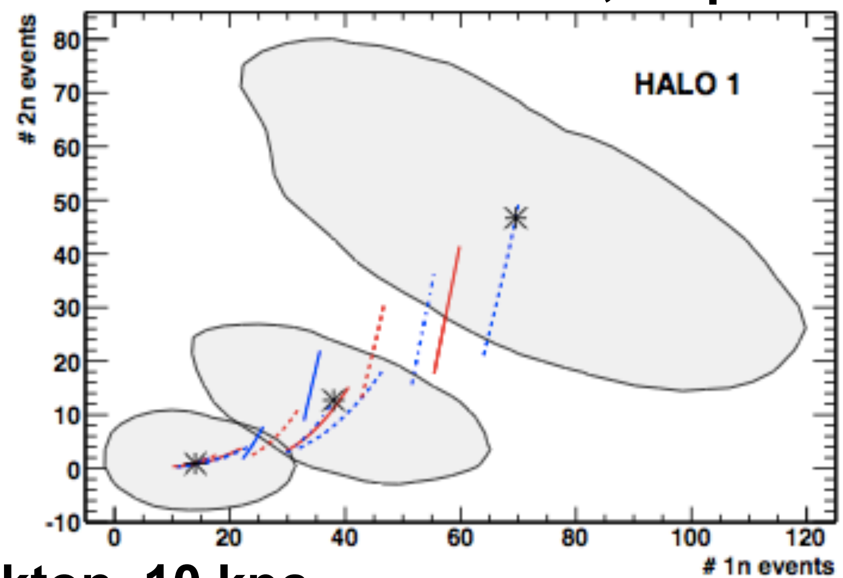
NEW

HALO sensitivity

79 tons, 10 kpc

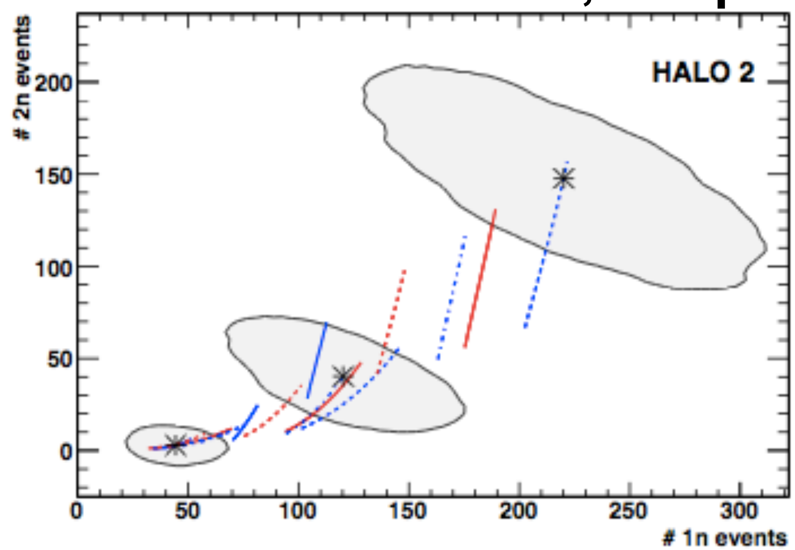


79 tons, 5 kpc



Note that measuring few events will give significant information

1kton, 10 kpc



- Curves represent predictions for a range of models with different fluxes and oscillation parameters, from Vaananen & Volpe arXiv:1105.6225
- Shaded regions enclose 90% of HALO inferred values, for simulated neutron detection efficiencies

Neutrino-nucleus NC elastic scattering in ultra-low energy detectors

$\nu_x + A \rightarrow \nu_x + \boxed{A}$

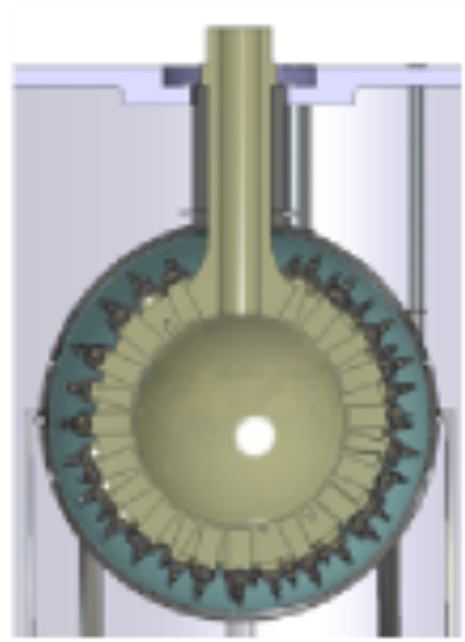
C. Horowitz et al., astro-ph/0302071

High x-scn but *very* low recoil energy (10's of keV)
$\Rightarrow$ possibly observable in solar pp/DM detectors

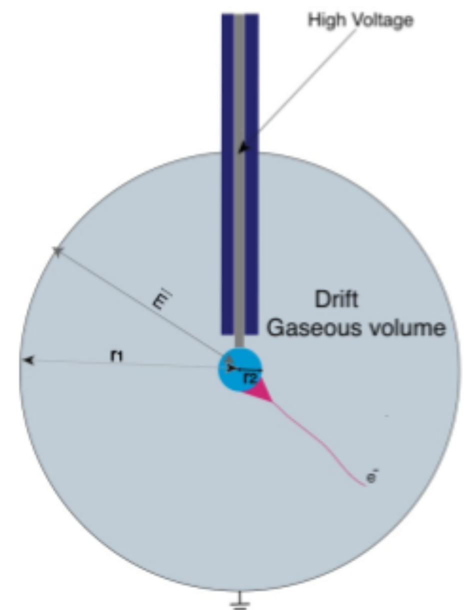
~ few events per ton for Galactic SN

ν_x energy information from recoil spectrum

e.g. Ar, Ne, Xe, Ge, ...



DM detectors, e.g. CLEAN/DEAP



Spherical Xe TPC
Aune et al.

Summary of SN neutrino detection channels

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

- dominates for detectors with lots of free p (water, scint)
- $\bar{\nu}_e$ sensitivity; good E resolution; well known x-scn; some tagging, poor pointing

CC interactions with nuclei:

- lower rates, but still useful, ν_e tagging useful (e.g. LAr)
- cross-sections not always well known

Elastic scattering: few % of invβdk, but point!

NC interactions with nuclei:

- very important for physics, probes μ and τ flux
- some rate in existing detectors, new observatories
- some tagging; poor E resolution; x-scns not well known
- coherent ν-p, ν-A scattering in low thresh detectors

KS, arXiv:1205.6003

Table 1 Summary of relevant interactions for current and near-future detectors

Channel	Observable(s)[a]	Interactions[b]
$\nu_x + e^- \to \nu_x + e^-$	C	17/10
$\bar{\nu}_e + p \to e^+ + n$	C, N, A	278/165
$\nu_x + p \to \nu_x + p$	C	682/351
$\nu_e + {}^{12}C \to e^- + {}^{12}N^{(*)}$	C, N, G	3/9
$\bar{\nu}_e + {}^{12}C \to e^+ + {}^{12}B^{(*)}$	C, N, G, A	6/8
$\nu_x + {}^{12}C \to \nu_x + {}^{12}C^*$	G, N	68/25
$\nu_e + {}^{16}O \to e^- + {}^{16}F^{(*)}$	C, N, G	1/4
$\bar{\nu}_e + {}^{16}O \to e^+ + {}^{16}N^{(*)}$	C, N, G	7/5
$\nu_x + {}^{16}O \to \nu_x + {}^{16}O^*$	G, N	50/12
$\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$	C, G	67/83
$\bar{\nu}_e + {}^{40}Ar \to e^+ + {}^{40}Cl^*$	C, A, G	5/4
$\nu_e + {}^{208}Pb \to e^- + {}^{208}Bi^*$	N	144/228
$\nu_x + {}^{208}Pb \to \nu_x + {}^{208}Pb^*$	N	150/55
$\nu_x + A \to \nu_x + A$	C	9,408/4,974

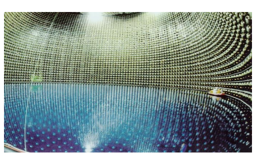
(Livermore/GKVM)

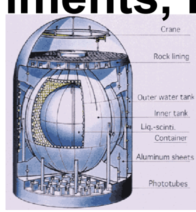
C: energy loss of a charged particle
N: neutrons
A: annihilation gammas
G: de-excitation gammas

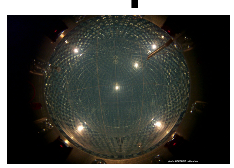
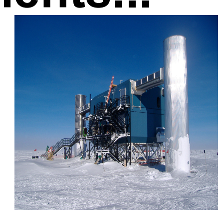
Current & near-future supernova neutrino detectors

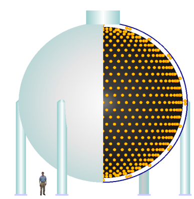
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
HALO	Lead	Canada	0.079	20	Running
Icarus	Liquid argon	Italy	0.6	(60)	(Running)
NOvA	Scintillator	USA	15	3000	Under construction
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction

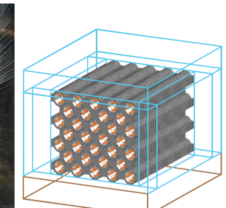
plus reactor experiments, DM experiments...









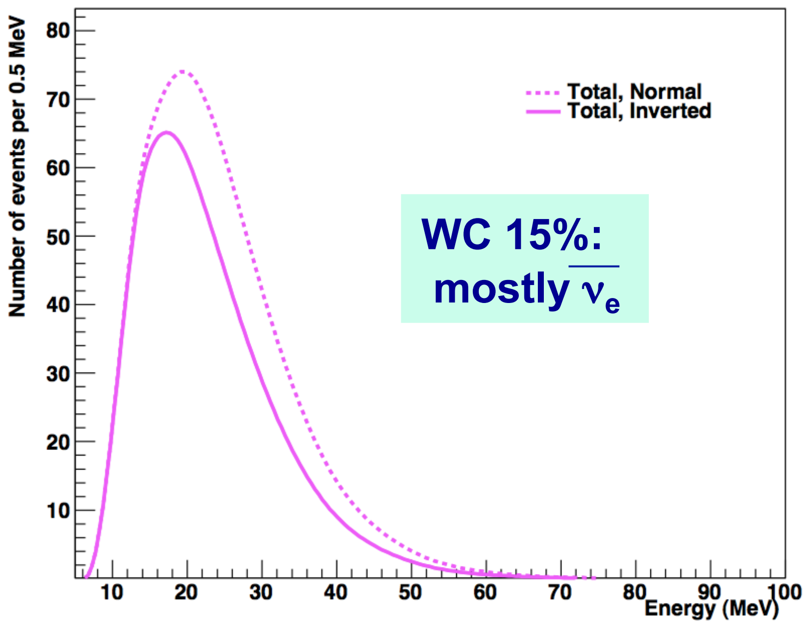
Primary sensitivity is to electron antineutrinos via inverse beta decay

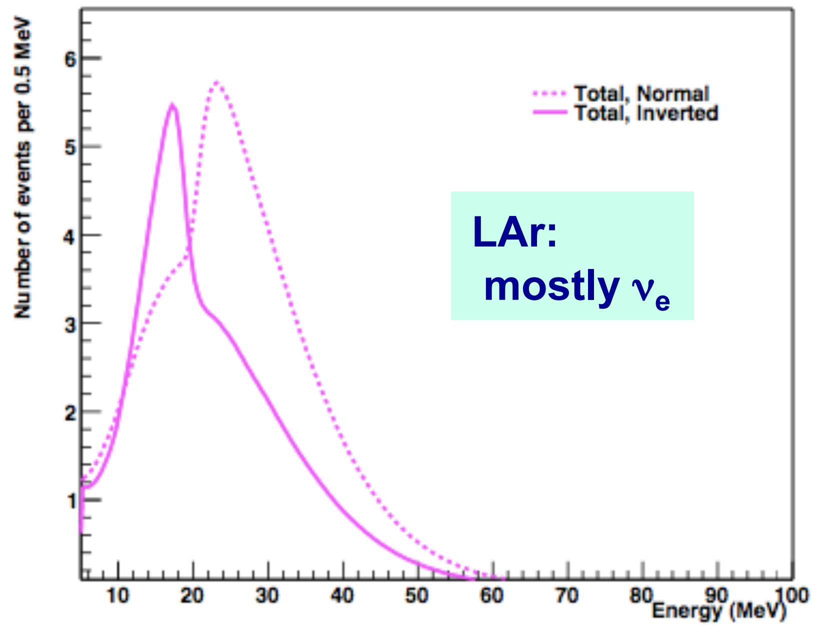
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Observability of oscillation features: example

Can we tell the difference between normal and inverted mass hierarchies?

(1 second late time slice, flux from H. Duan w/collective effects)





Differences, but no sharp features

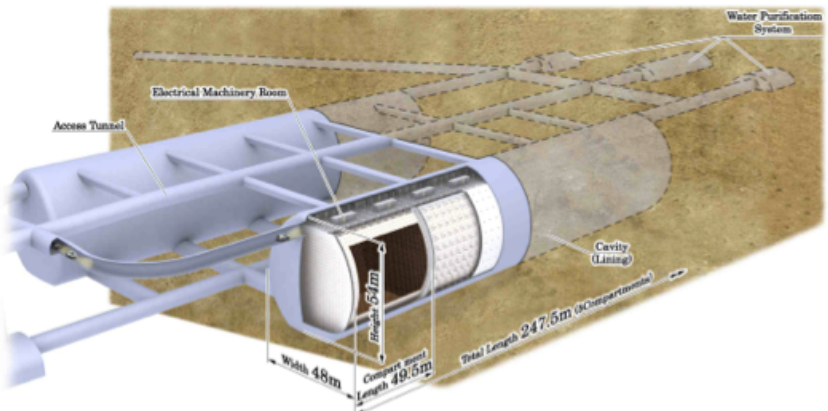
LAr shows dramatic difference

`Anecdotal' evidence is good... systematic surveys underway

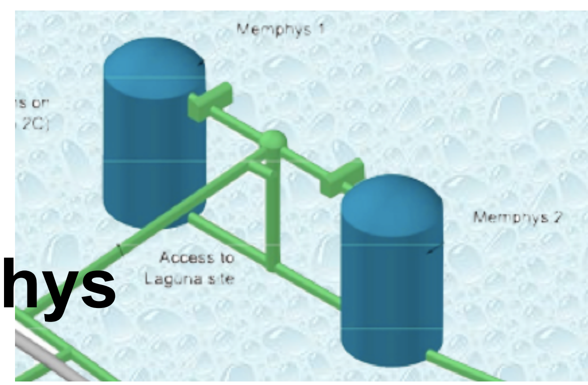
Diverse supernova detectors are desirable for getting the most physics from the burst

Next generation mega-detectors (10-20 years)

(LBNE WCh)

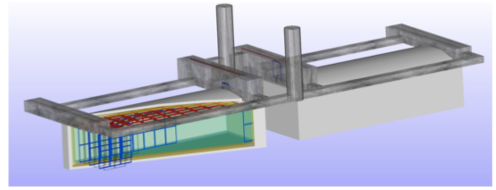


Hyper-K

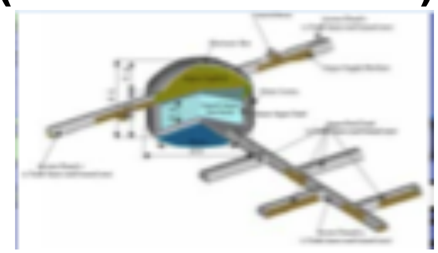


Memphys

Megaton-scale water detector concepts

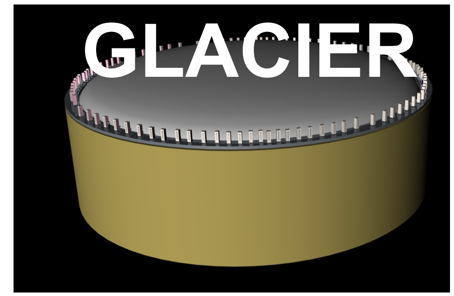


LBNE LAr (mass? surface?)



Okinoshima

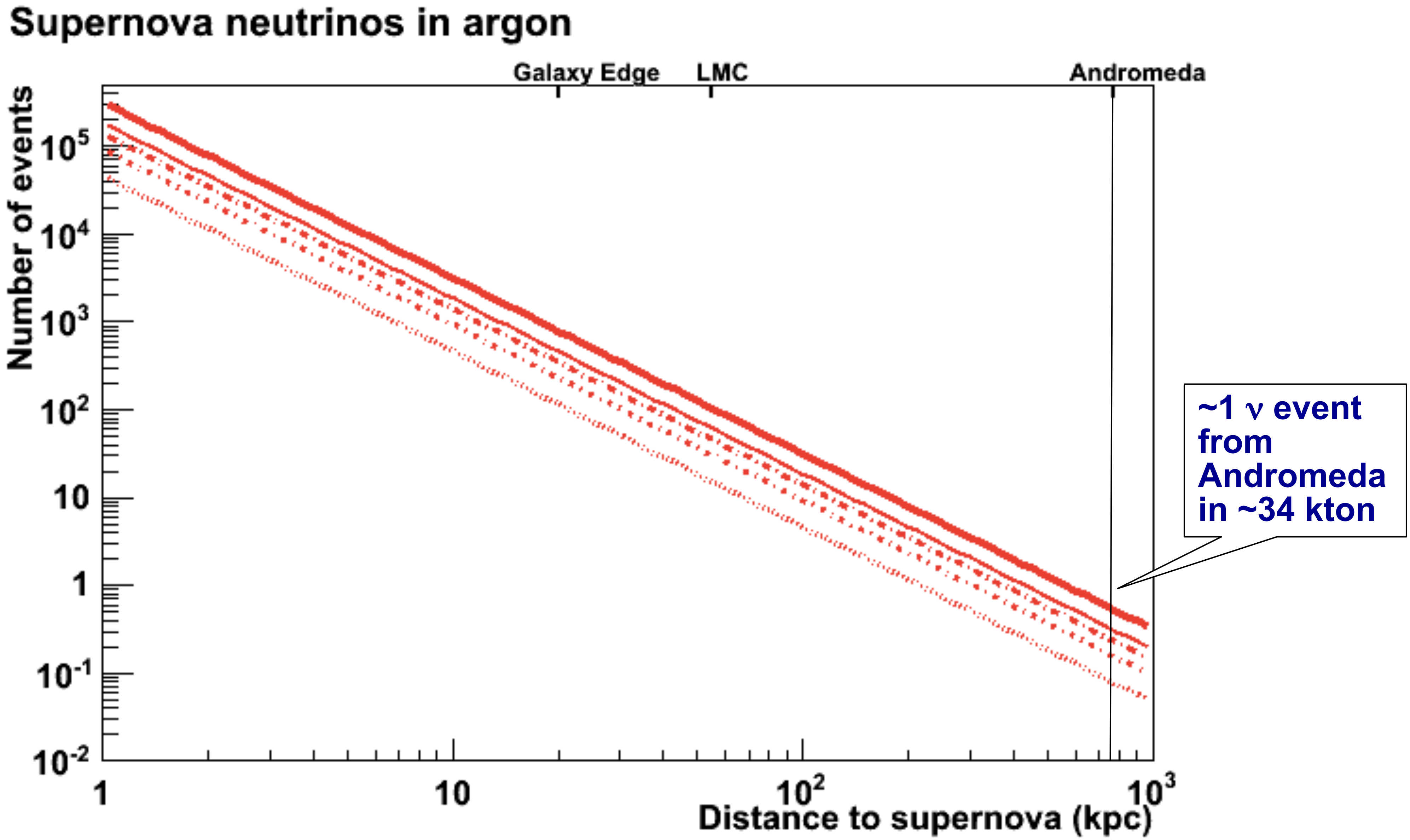
5-100 kton-scale liquid argon concepts



10-100 kton-scale scintillator detector concepts

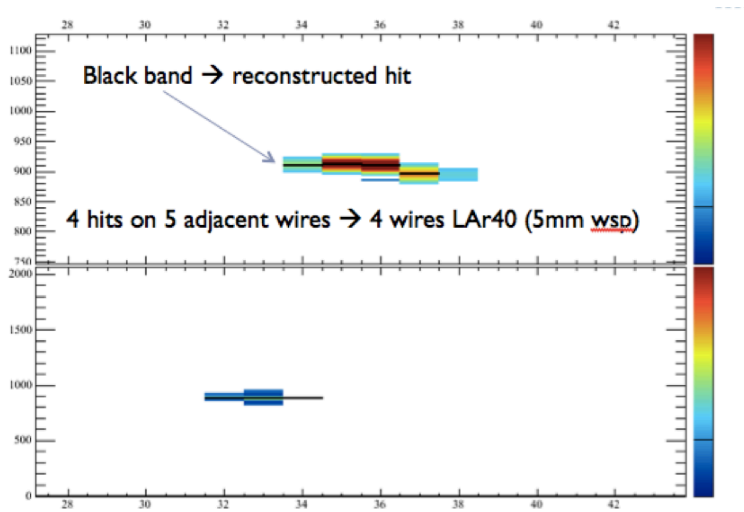
LENA

Signal rates vs distance for LBNE configurations



5, 10, 15, 20, 34 kton

SN signal and background in LAr



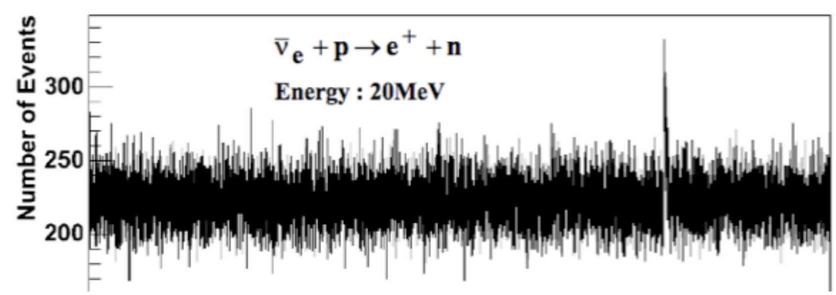
Note:

may also have γ tag for CC interactions

- **muons & associated Michels: should be identifiable**
- **radioactivity: mostly < 5 MeV**
- **cosmogenics**

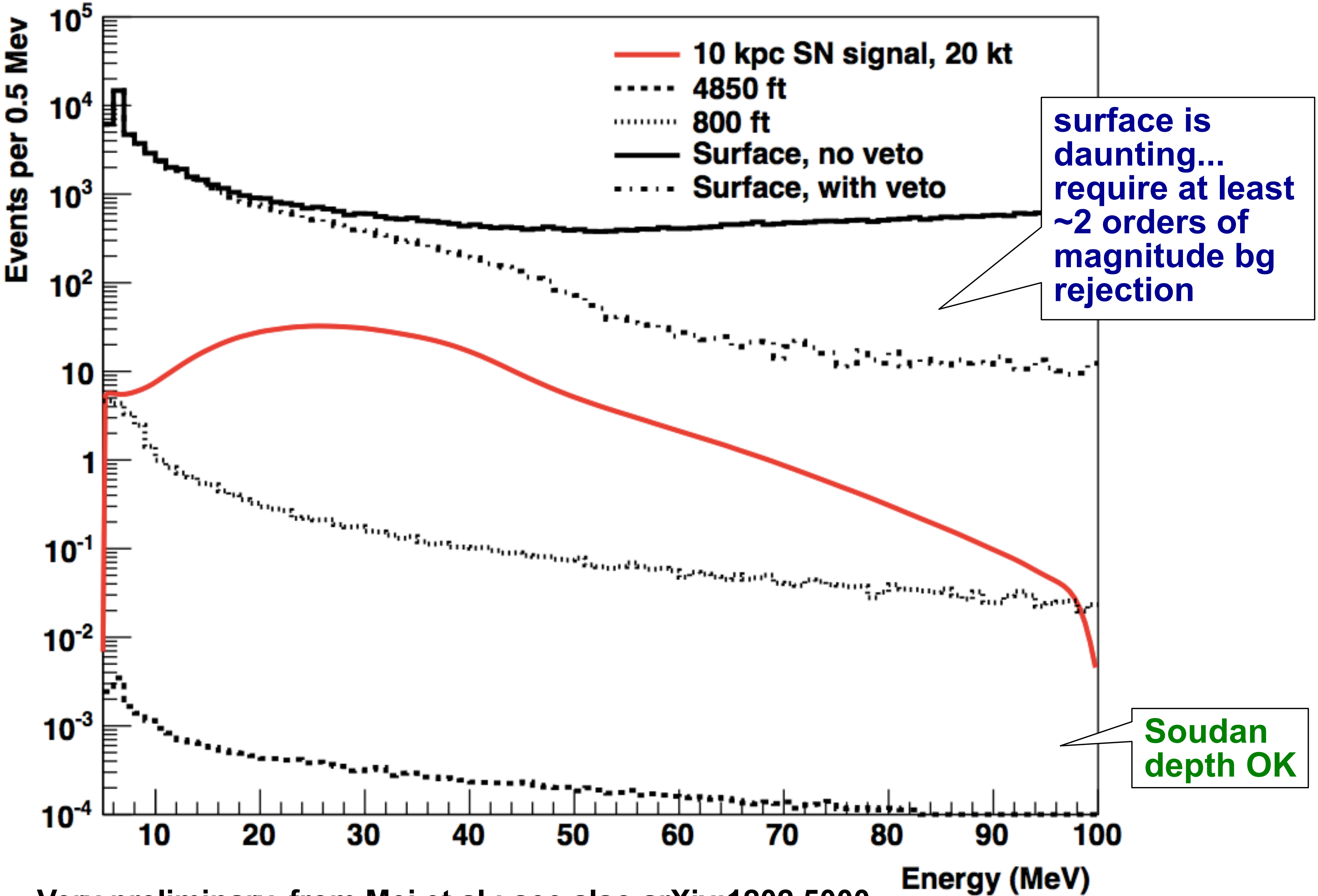
How shallow is OK?

NOνA, MiniBooNE, μBooNE get *something*, if background-ridden (and bg can be *known*)



NOνA

Muon-induced fast neutron background



Very preliminary, from Mei et al.: see also arXiv:1202.5000

Summary of supernova neutrino detectors

Galactic sensitivity

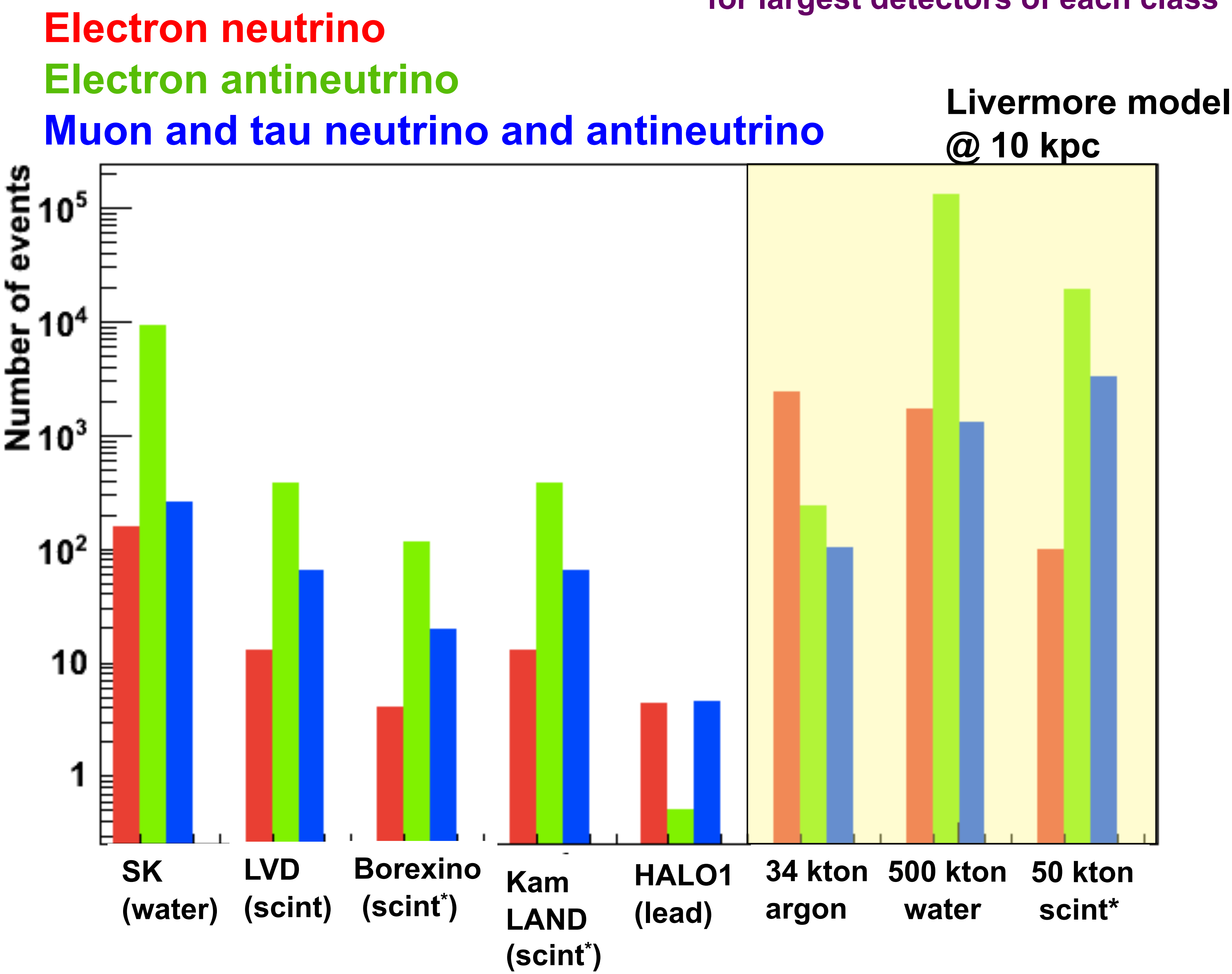
Extragalactic

Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	Running
HALO	Lead	Canada	0.079	20	Running
Icarus	Liquid argon	Italy	0.6	(60)	(Running)
NOνA	Scintillator	USA	15	3000	Under construction
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
LBNE LAr	Liquid argon	USA	34	3000	Proposed
(LBNE WC)	Water	USA	200	44,000	Proposed
MEMPHYS	Water	Europe	440	88,000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
LENA	Scintillator	Europe	50	15,000	Proposed
GLACIER	Liquid argon	Europe	100	9000	Proposed

plus reactor experiments, DM experiments...

World SN flavor sensitivity

for largest detectors of each class



* plus NC ν-p scattering

Summary of Part I

Current detectors:

- ~Galactic sensitivity
  (SK reaches barely to Andromeda)
- sensitive mainly to the $\bar{\nu}_e$ component of the SN flux
- excellent timing from IceCube
- early alert network is waiting

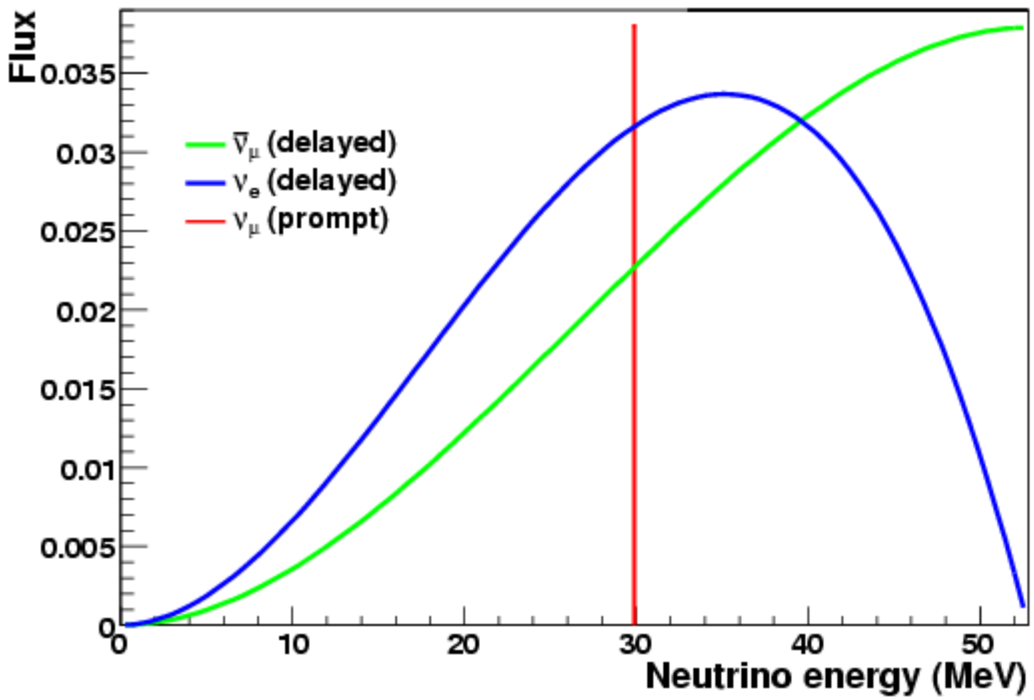
Near future

- more flavor sensitivity (e.g. HALO)

Farther future, for megadetectors

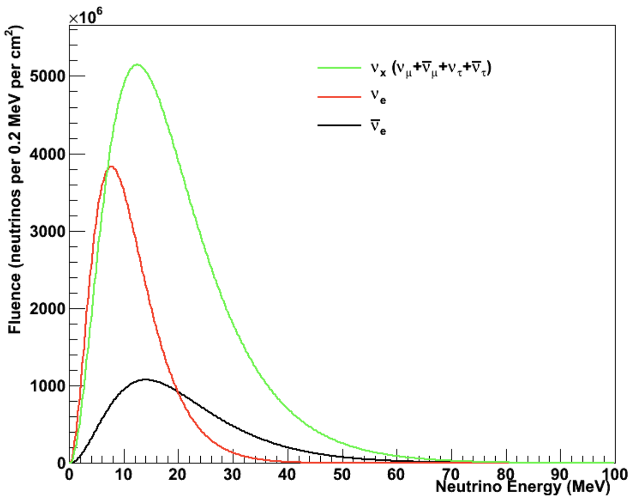
- extragalactic reach, DSNB
- huge statistics, richer flavor sensitivity
- excellent oscillation sensitivity

Part II: Neutrino-Nucleus Cross-Sections with a Decay-at-Rest Neutrino Source

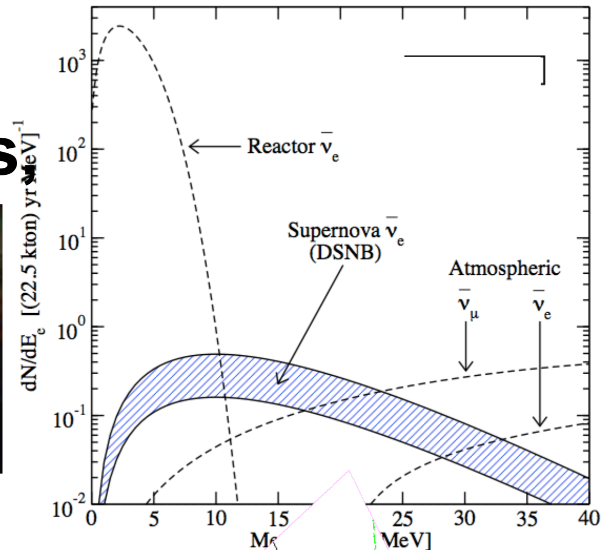


- supernova-related studies
- coherent NC scattering
- (neutrino oscillation, and more)

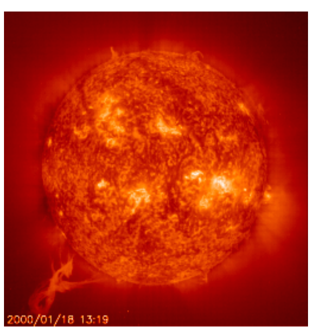
Neutrino interactions in the few-100 MeV range are relevant for:

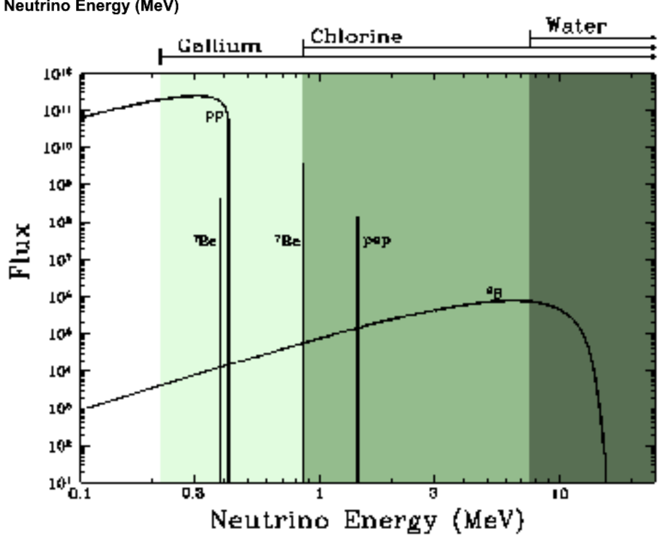


supernova neutrinos burst & relic

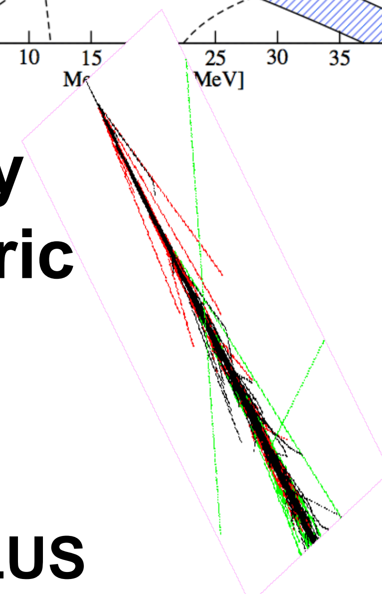


solar neutrinos

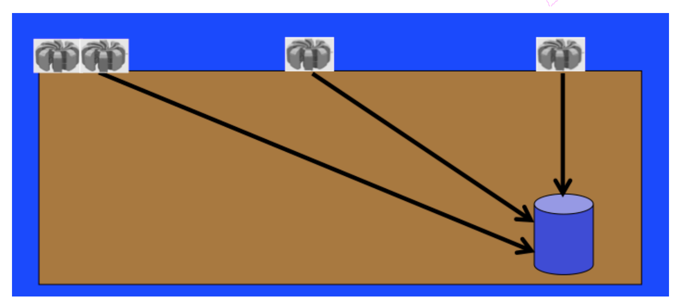




low energy atmospheric neutrinos

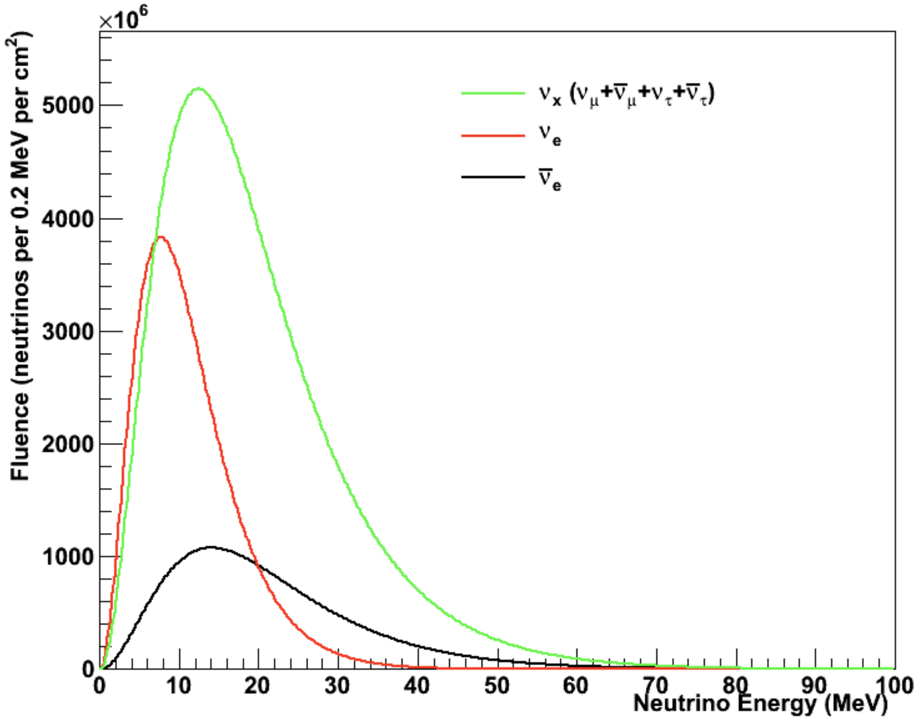


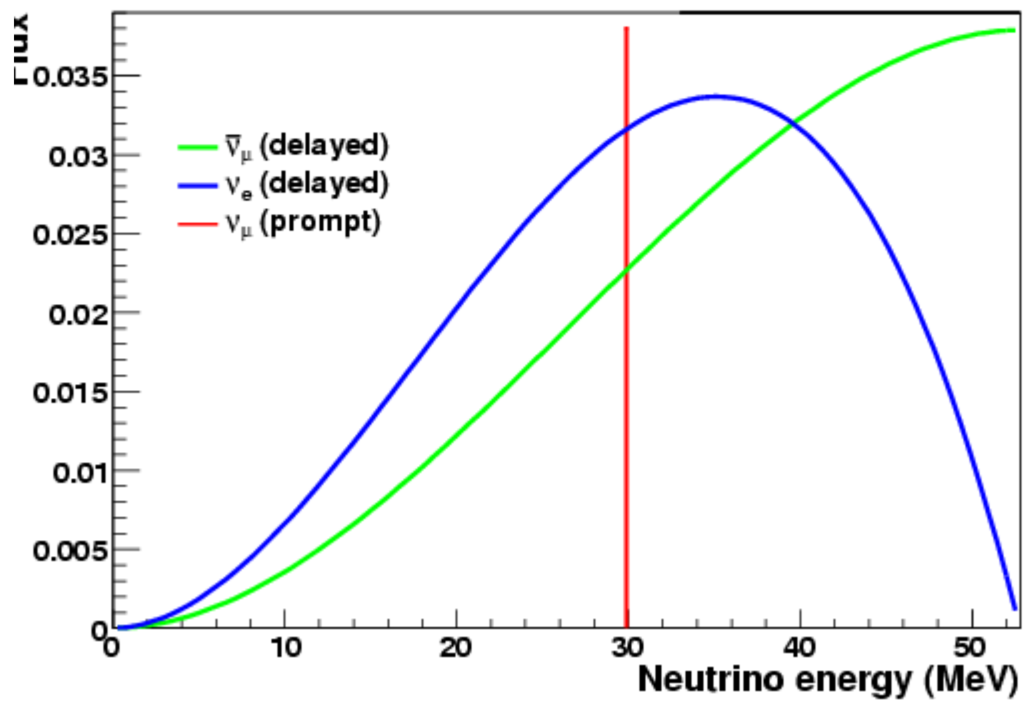
DAEdALUS



oscillation, astrophysics

Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum

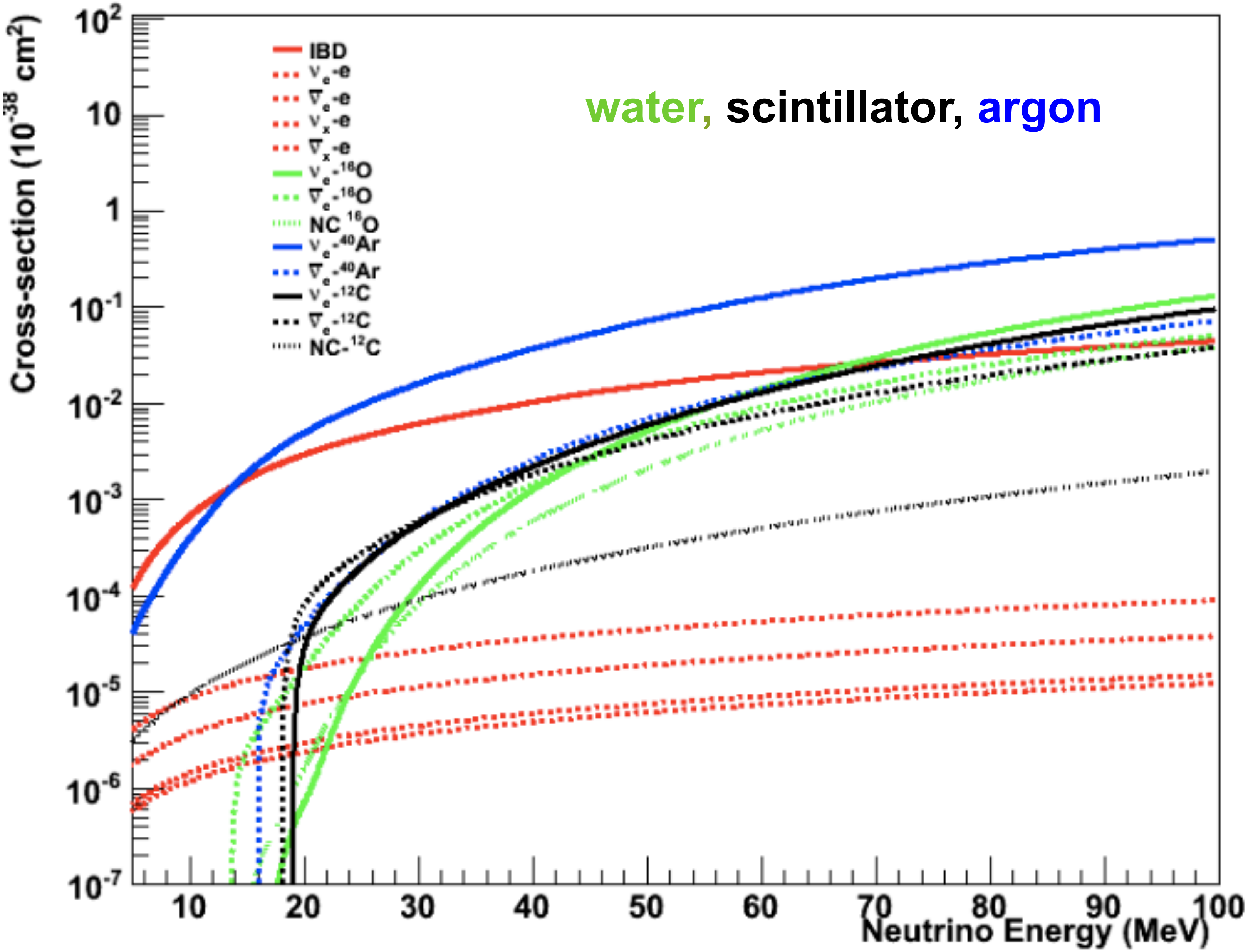




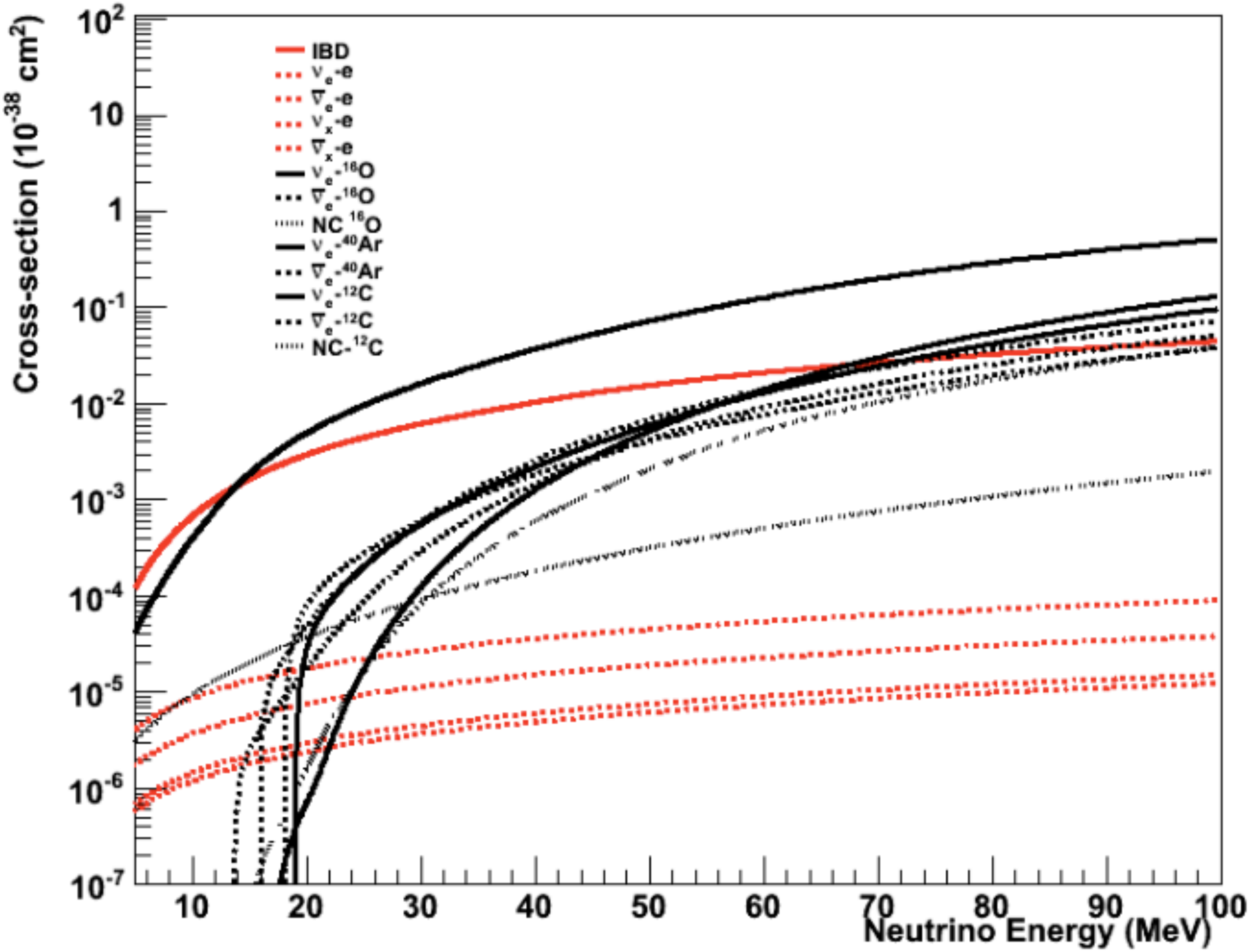
Study CC and NC interactions with various nuclei, in few to 10's of MeV range

1. **Understanding of *core-collapse SN processes*, nucleosynthesis**
2. **Understanding of *SN ν detection* processes**

Cross-sections in this energy range



The old friends: inverse beta decay, neutrino-electron elastic scattering; known at few % level

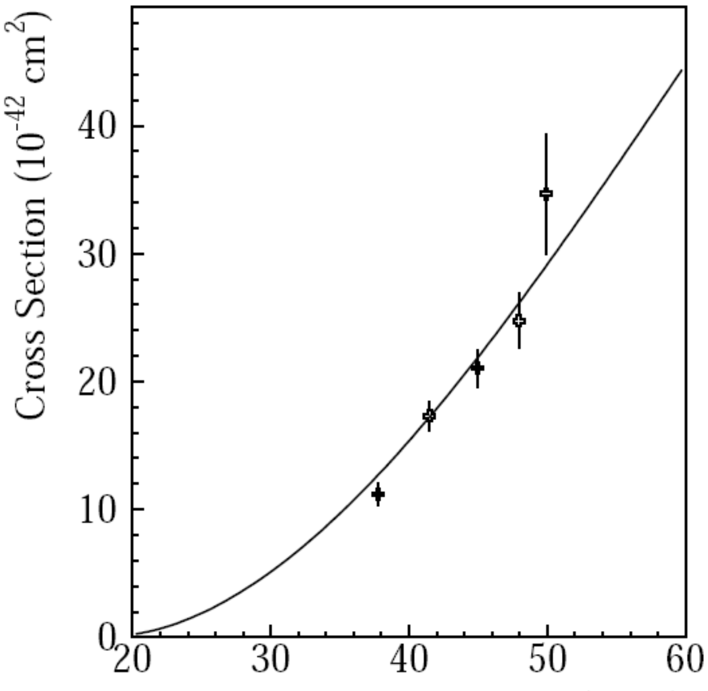


So far only ^{12}C is the *only* heavy nucleus with ν interaction x-sections well (~10%) measured in the tens of MeV regime

e.g.

LSND

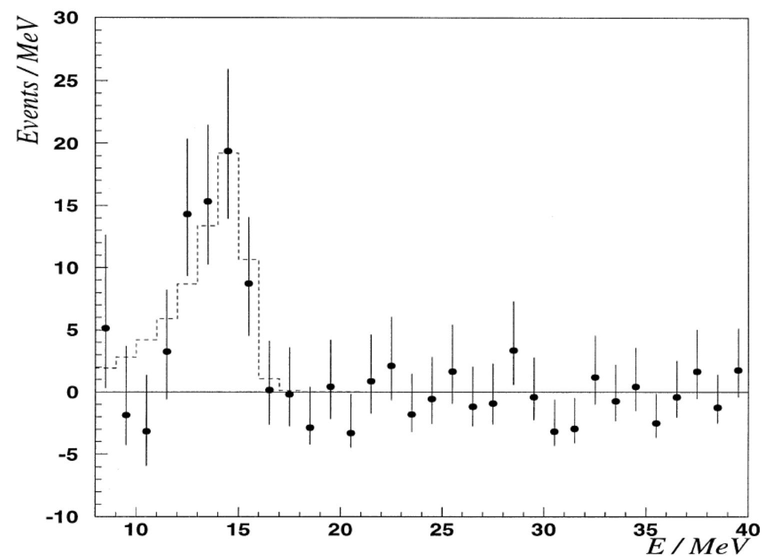
Phys. Rev. C 66 (2002) 015501



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

Karmen

Phys. Lett. B 423 (1998) 15-20

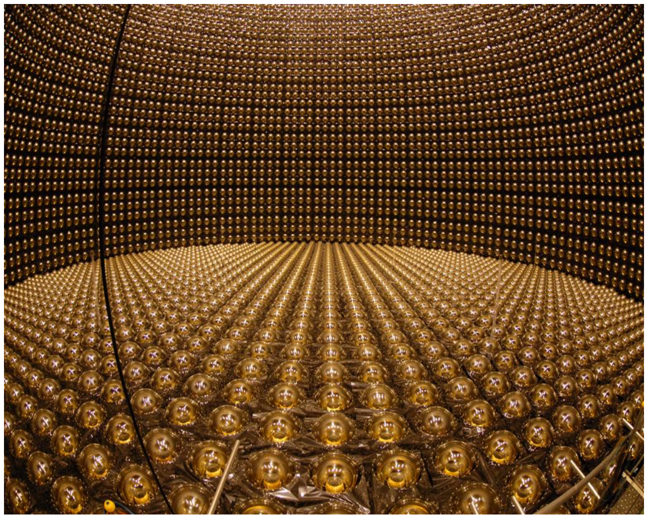


$$^{12}\mathrm{C}(\nu_\mu \nu'_\mu)\,^{12}\mathrm{C}^*(1^+, 1; 15.1\ \mathrm{MeV})$$

Need: oxygen (water), lead, iron, argon...

<u>Example 1</u>: interactions on oxygen nuclei

CC interactions



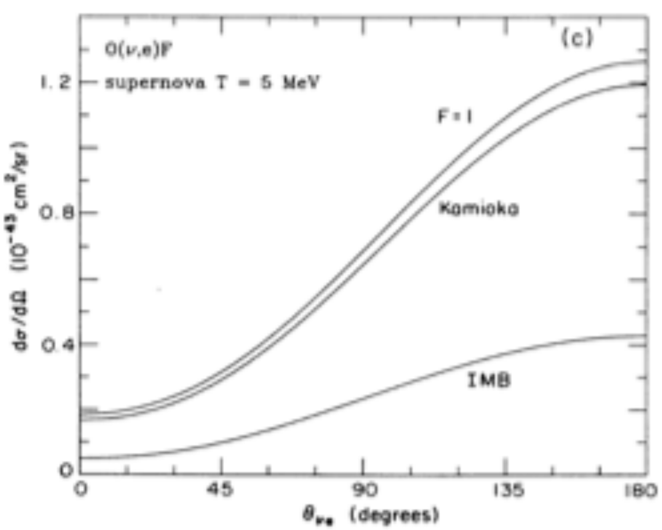
few % of SN signal

Kolbe, Langanke, Vogel: PRD 66, (2002) 013007

TABLE III. Partial cross sections for charged-current neutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=4$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

Neutrino reaction	$\sigma, T=4$ MeV	$\sigma, T=8$ MeV
total	1.91 (−1)	1.37 (+1)
$^{16}O(\nu_e,e^-p)^{15}O(g.s.)$	1.21 (−1)	6.37 (+0)
$^{16}O(\nu_e,e^-p\gamma)^{15}O^*$	4.07 (−2)	3.19 (+0)
$^{16}O(\nu_e,e^-np)^{14}O^*$	3.92 (−4)	1.76 (−1)
$^{16}O(\nu_e,e^-pp)^{14}N^*$	2.61 (−2)	3.26 (+0)
$^{16}O(\nu_e,e^-\alpha)^{12}N^*$	1.16 (−3)	1.31 (−1)
$^{16}O(\nu_e,e^-p\alpha)^{11}C^*$	2.17 (−3)	5.66 (−1)
$^{16}O(\nu_e,e^-n\alpha)^{11}N(p)^{10}C^*$	1.11 (−6)	3.28 (−3)

Angular distributions are interesting



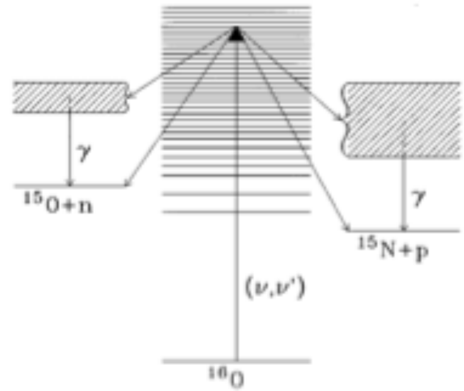
Haxton: PRD 36, (1987) 2283

TABLE IV. Partial cross sections for charged-current antineutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=5$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

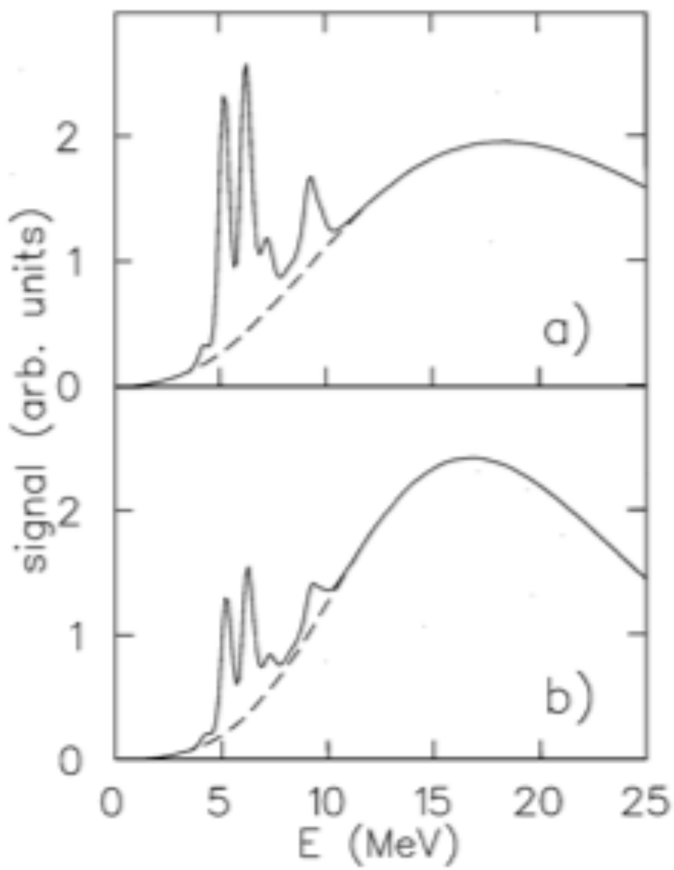
Neutrino reaction	$\sigma, T=5$ MeV	$\sigma, T=8$ MeV
total	1.05 (+0)	9.63 (+0)
$^{16}O(\bar{\nu}_e,e^+)^{16}N(g.s.)$	3.47 (−1)	2.15 (+0)
$^{16}O(\bar{\nu}_e,e^+n)^{15}N(g.s.)$	5.24 (−1)	4.81 (+0)
$^{16}O(\bar{\nu}_e,e^+n\gamma)^{15}N^*$	1.47 (−1)	1.90 (+0)
$^{16}O(\bar{\nu}_e,e^+np)^{14}C^*$	4.56 (−3)	1.38 (−1)
$^{16}O(\bar{\nu}_e,e^+nn)^{14}N^*$	5.50 (−3)	1.81 (−1)
$^{16}O(\bar{\nu}_e,e^+\alpha)^{12}B^*$	1.07 (−2)	1.91 (−1)
$^{16}O(\bar{\nu}_e,e^+n\alpha)^{11}B^*$	6.20 (−3)	2.16 (−1)

NC interactions on oxygen nuclei

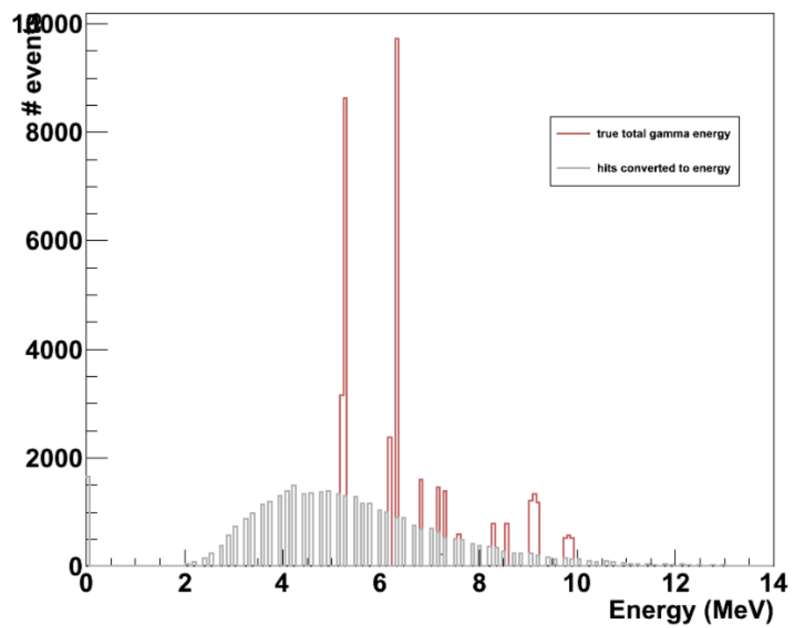
Final states from NC excitation



Langanke, Vogel, Kolbe: PRL 76, (1996) 2629

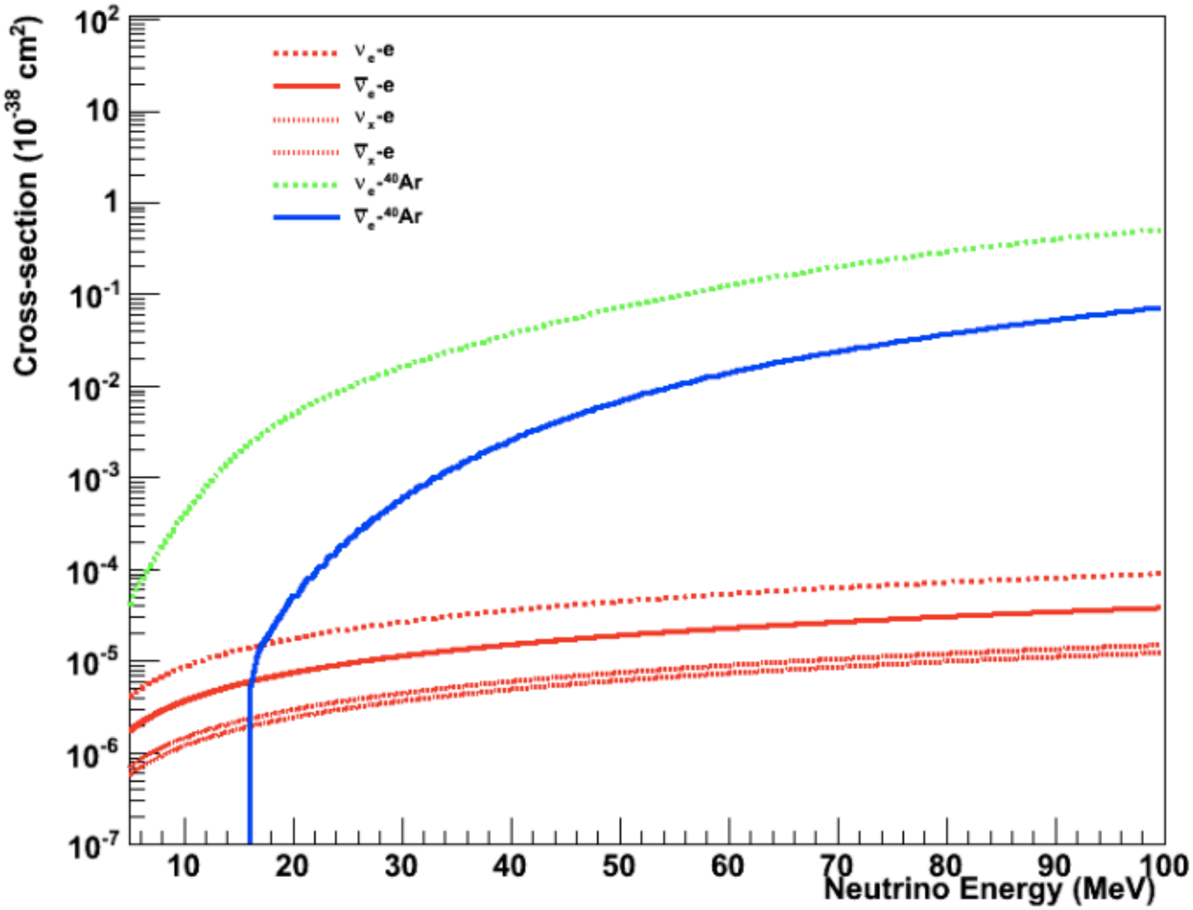


Observed γ energy per event



large fraction of the γ energy is lost in Compton scatter

Example 2: interactions on argon nuclei



M. Sajjad-Athar & S.K. Singh,
Phys. Lett. B 591 (2004) 69

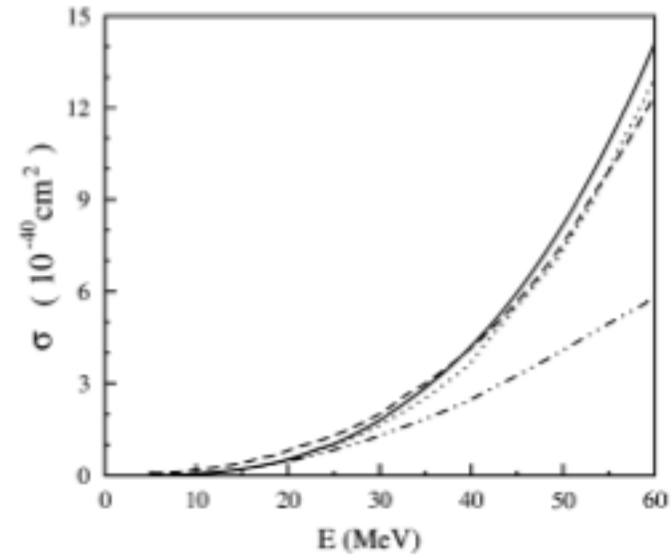
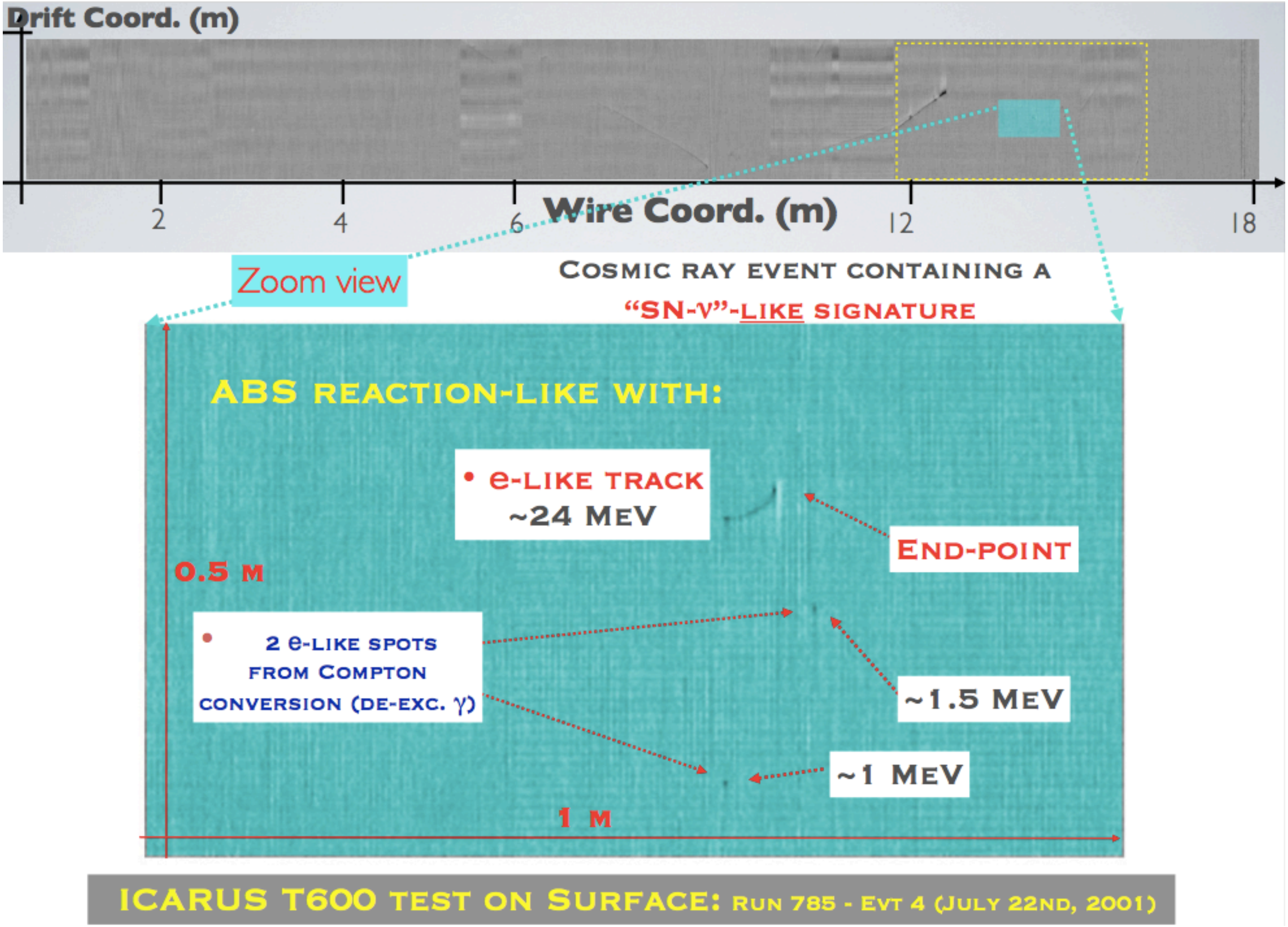


Fig. 3. Total cross section σ vs. E for $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ reaction with Fermi function (solid line), modified effective momentum approximation (dashed line), Ormand et al. [12] (dashed-double dotted line) and Bueno et al. [13] (dotted line).

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$
$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$$
$$\nu_x + {}^{40}\mathrm{Ar} \rightarrow \nu_x + {}^{40}\mathrm{Ar}^*$$

Again, final states include ejected nucleons and deexcitation γ's
... are these observable?

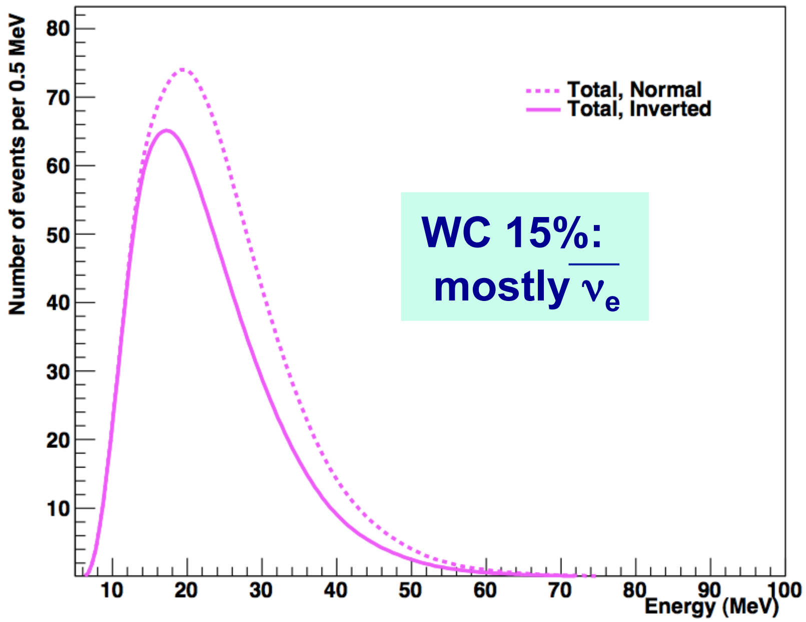
From Flavio Cavanna (SNS workshop, May 2012)

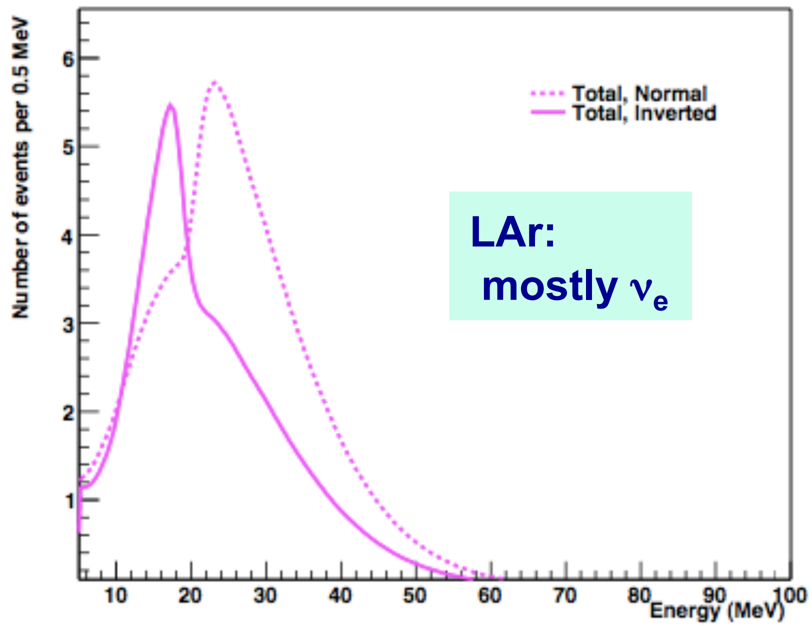


Observability of oscillation features: example

Can we tell the difference between normal and inverted mass hierarchies?

(1 second late time slice, flux from H. Duan w/collective effects)





Differences, but no sharp features

LAr shows dramatic difference

But need to understand the cross-section!

Example 3: Interactions on lead nuclei

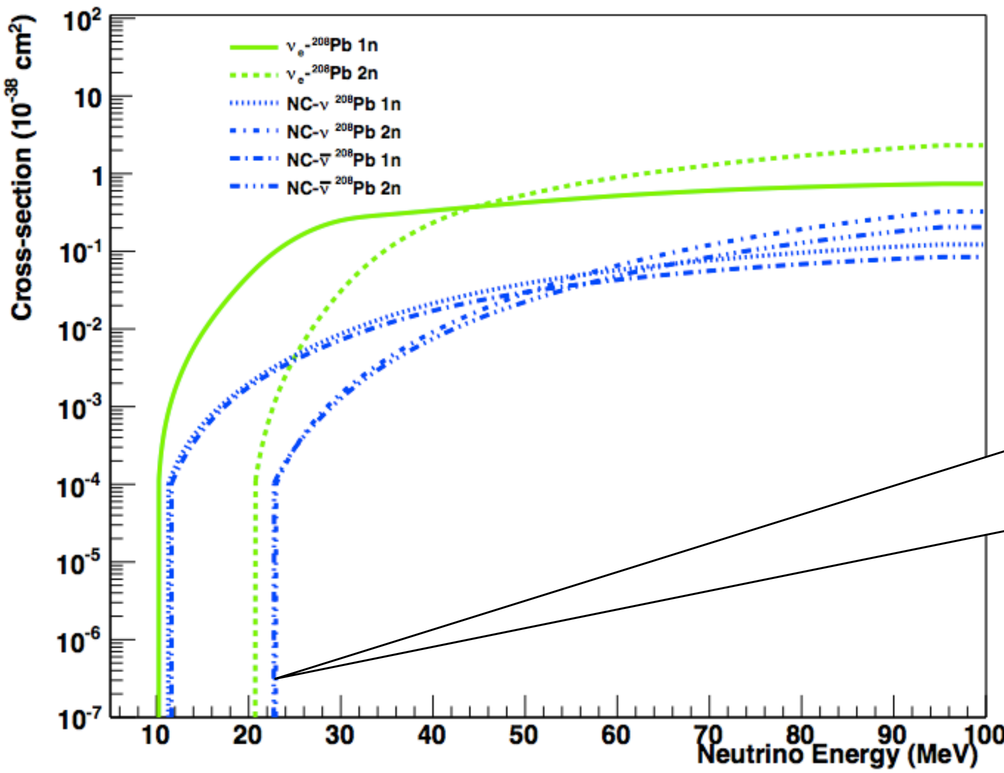
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

1n, 2n, γ emission

Observe single and double ~few MeV neutron events in the ^{3}He counters



sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

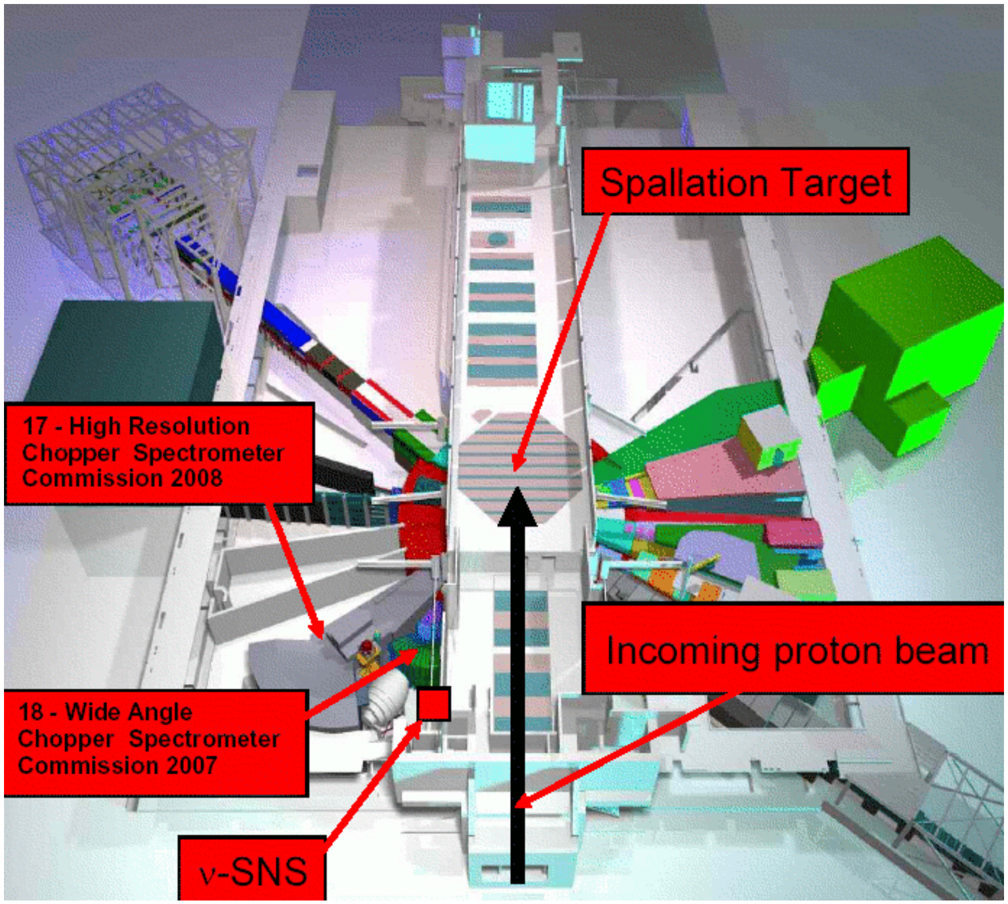
(similar for other lead isotopes)

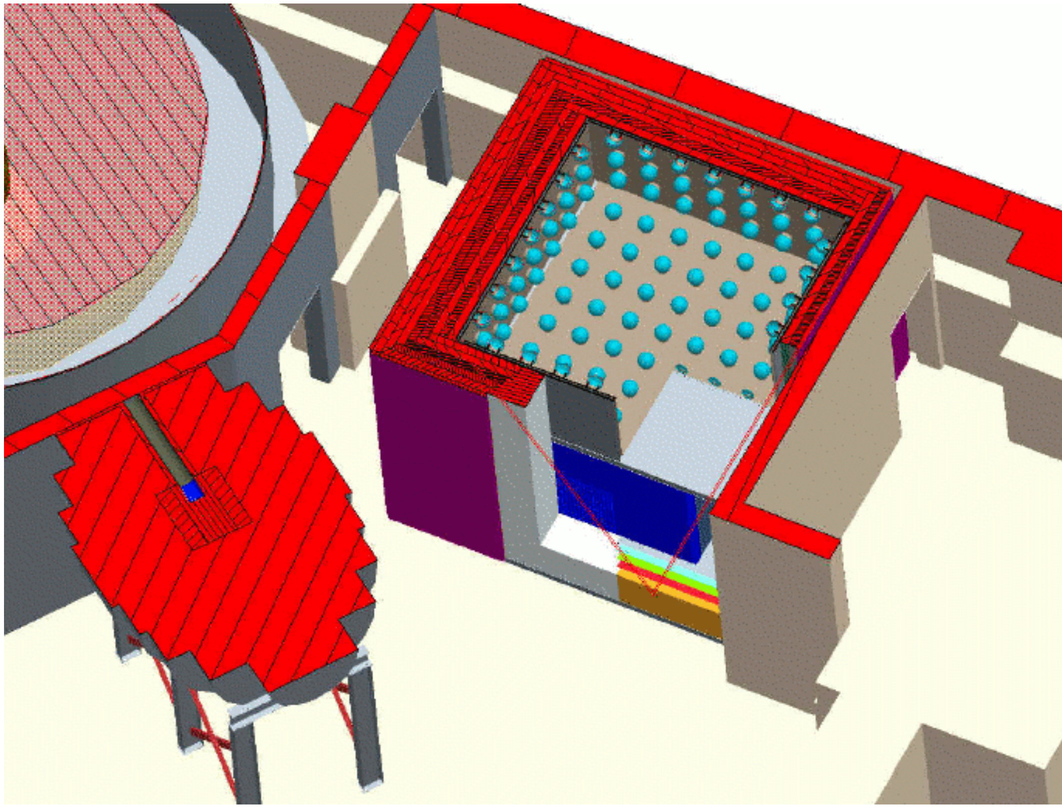
NuSNS (Neutrinos at the SNS)

Conventional ~10 ton detectors w/ few MeV thresholds:

- **-liquid target + PMTs**
- **-strawtube gas tracker+ target sheets**
- **-cosmic ray veto**

} changeable targets



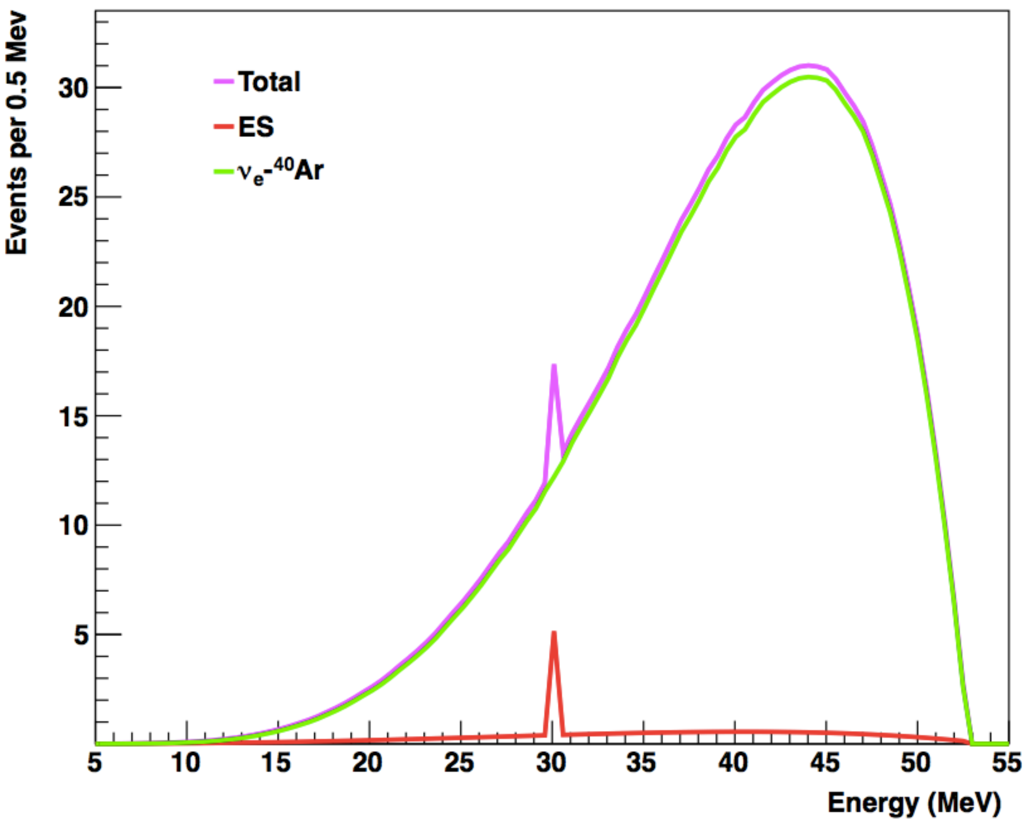


~2008 proposal; some activity now reviving

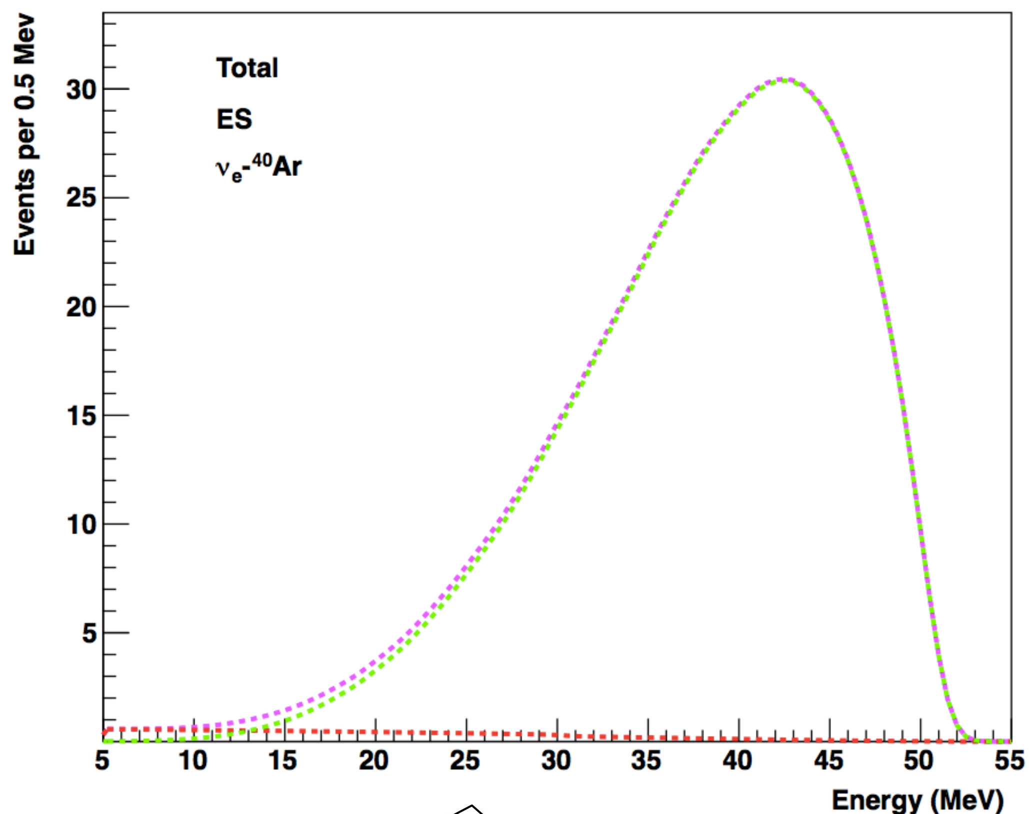
Event rates for argon at the SNS

per ton per year at 20 m

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy

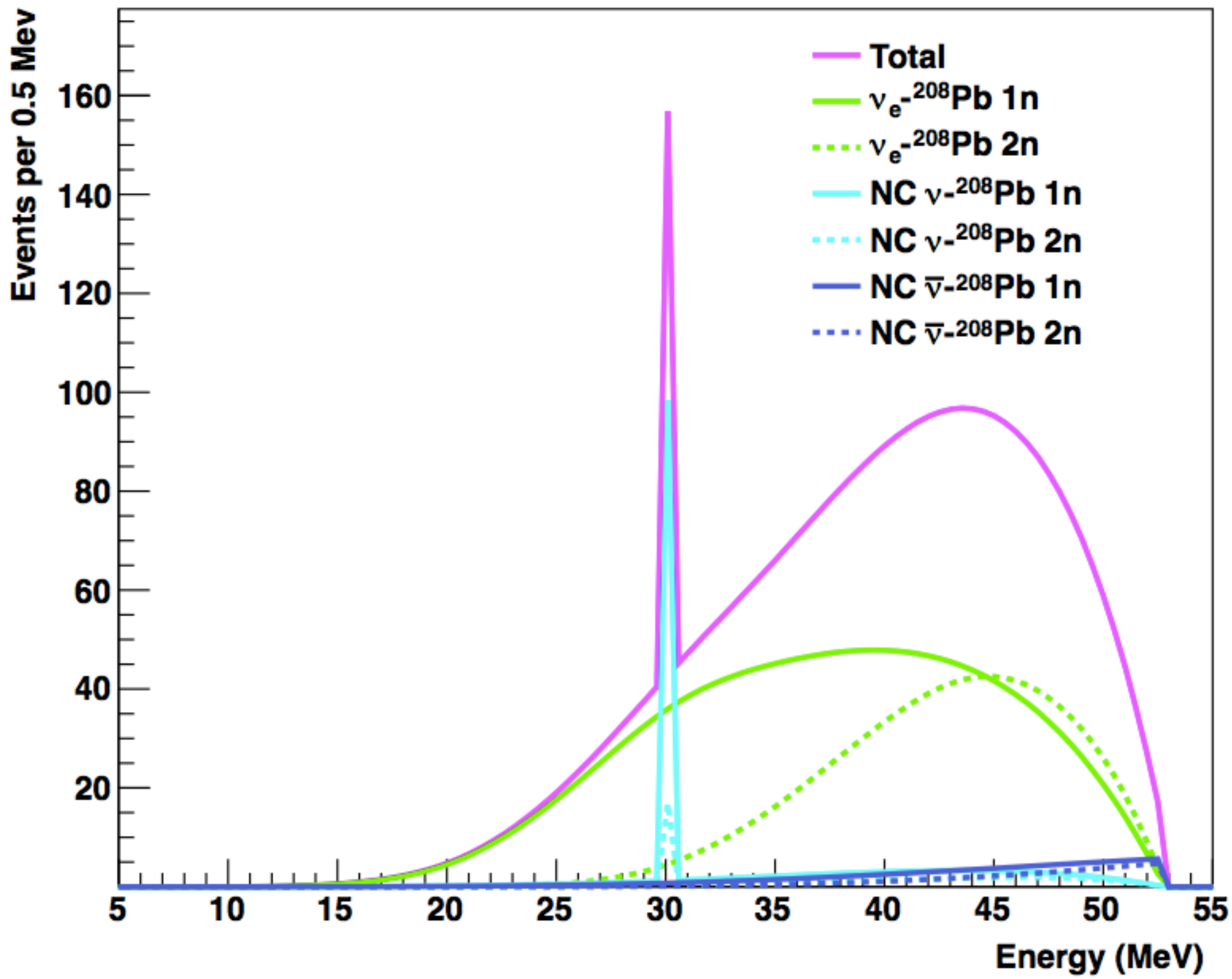


Assumes 100% efficiency,resolution from Amoruso et. al. (ICARUS)

Event rates for lead at the SNS

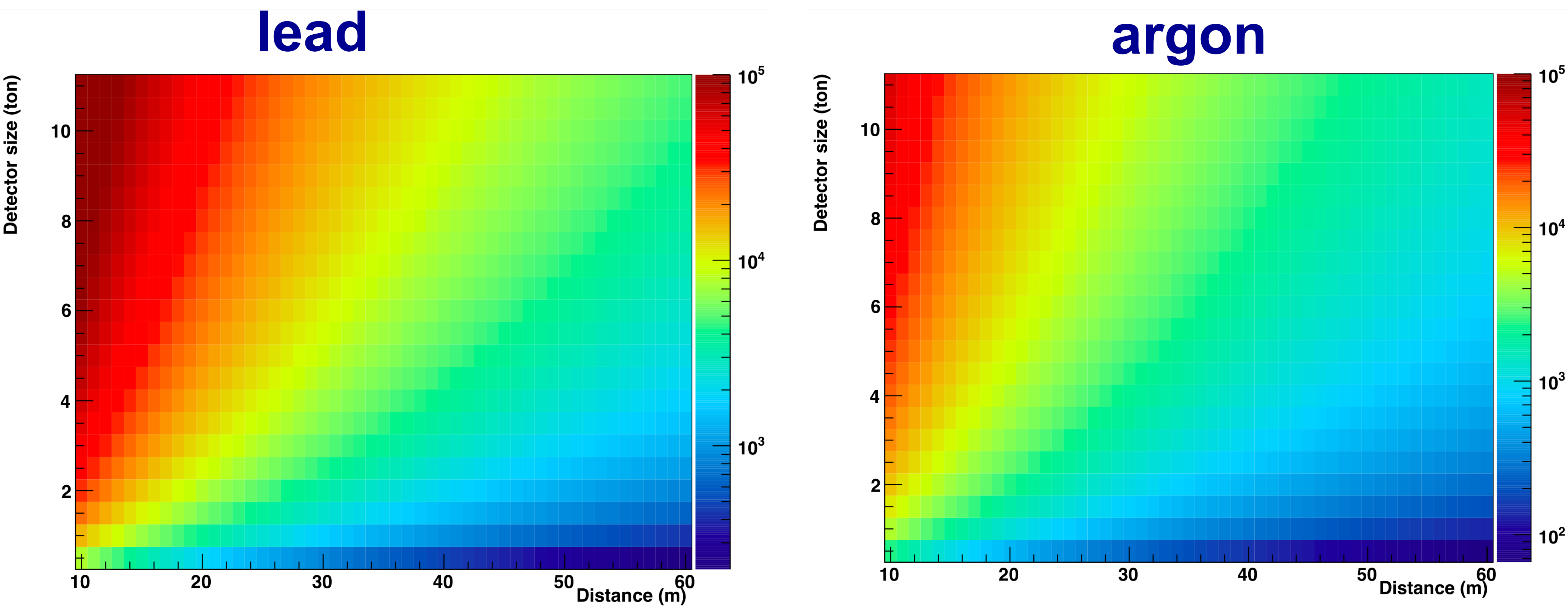
per ton per year at 20 m

Interactions, as a function of neutrino energy



Total events per year at the SNS as a function of distance and mass

$$\propto 1/R^2, \propto M$$

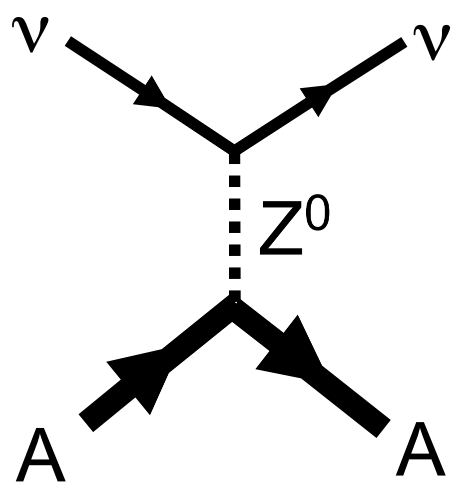


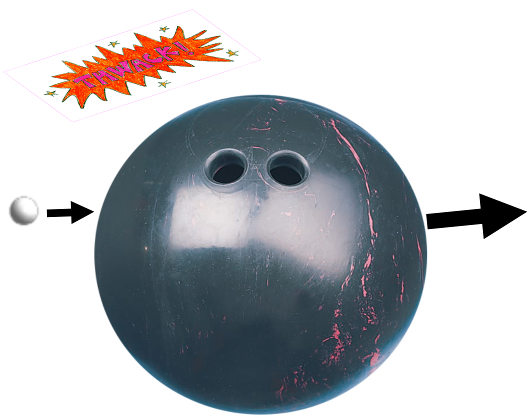
Scaling for another source: ~ power; duty factor is critical for background rejection

Coherent neutral current neutrino-nucleus elastic scattering

$$\nu + A \rightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils



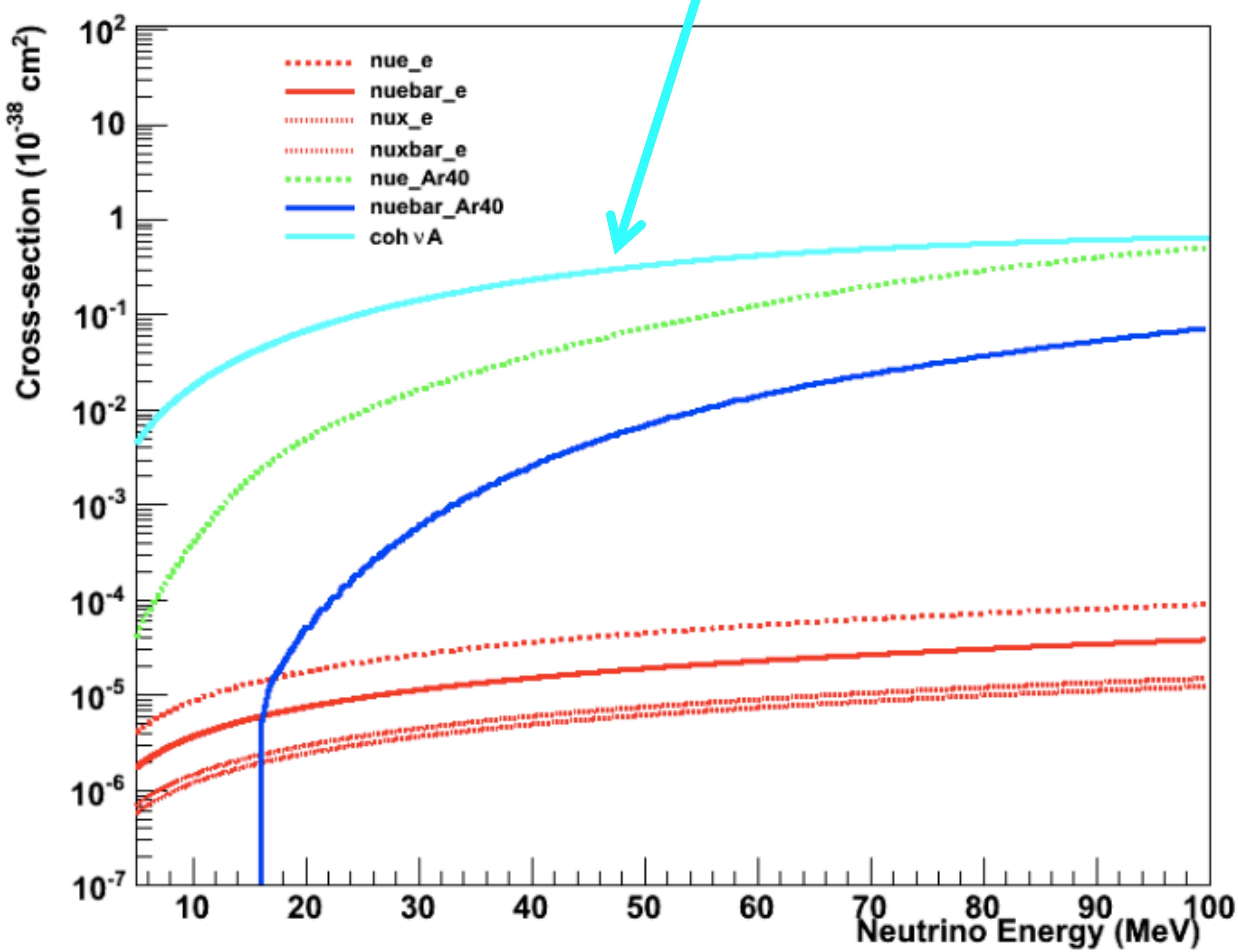


- **Coherent up to $E_\nu \sim 50$ MeV**
- **Important in SN processes & detection**
- **Well-calculable cross-section in SM**

A. Drukier & L. Stodolsky, PRD 30:2295 (1984)
Horowitz et al. , PRD 68:023005 (2003) astro-ph/0302071

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

And the cross-section is *large!*



Talk by Josh Spitz next

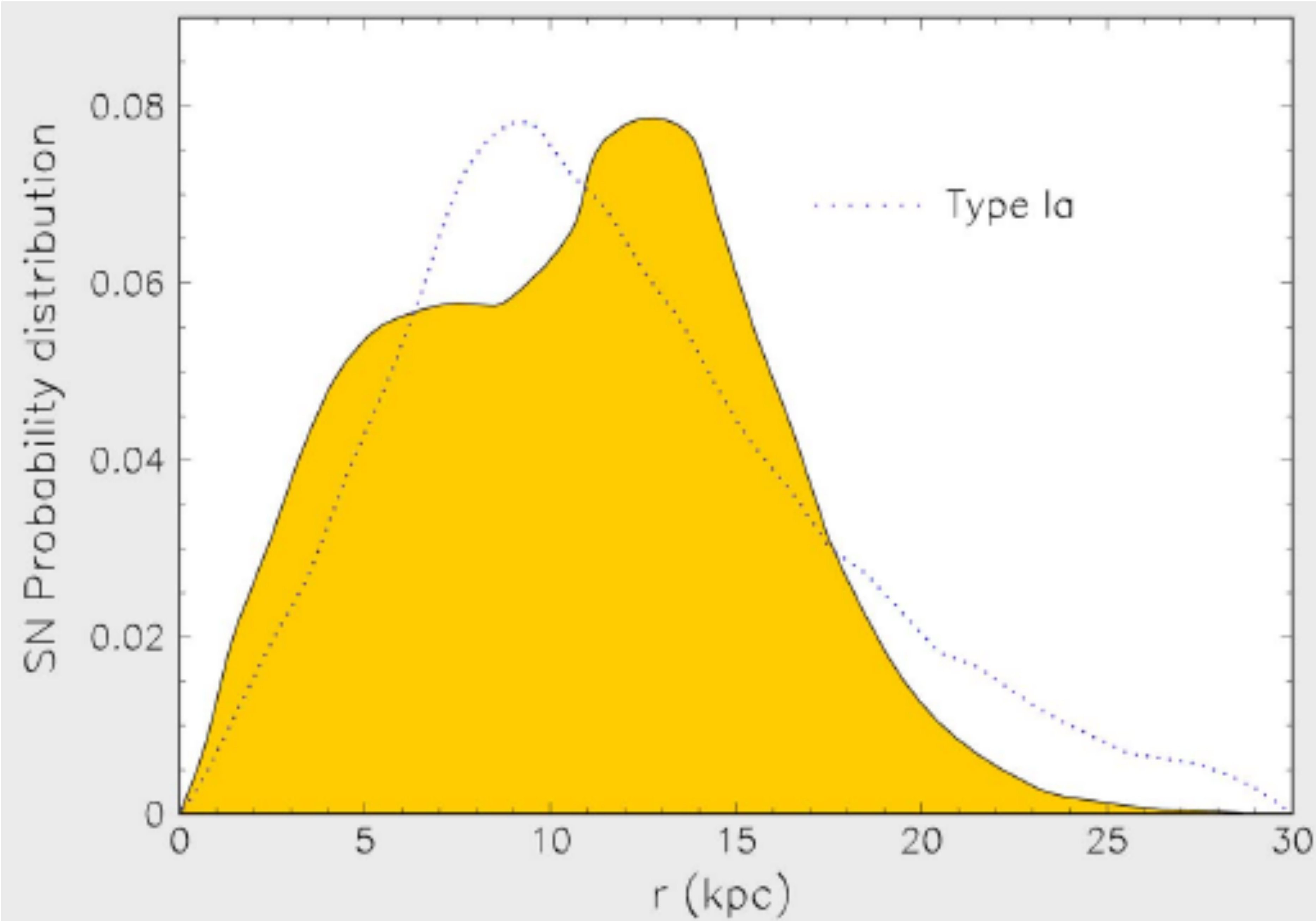
Summary of Part II

Neutrino-nucleus cross-sections are essentially unknown in the few-100 MeV regime!

A high-intensity, preferably pulsed, stopped-pion source offers excellent prospects for measurements in support of supernova (and other) physics

Extras/Backups

Typical distance from us: ~10-15 kpc



Mirizzi, Raffelt and Serpico , astro-ph/0604300

Possible enhancement:

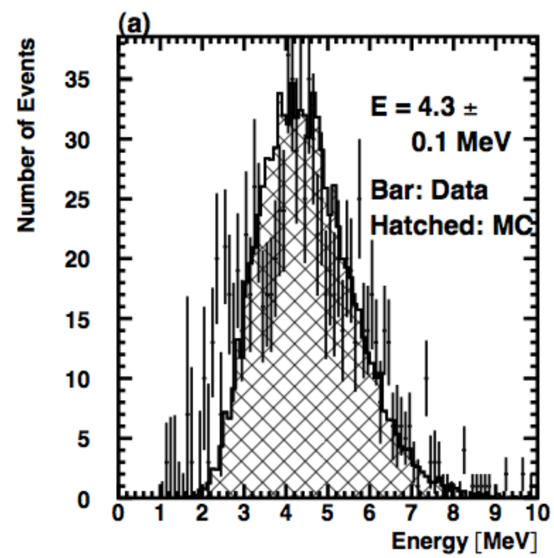
use gadolinium to capture neutrons for tag of $\bar{\nu}_e$

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons;

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma \qquad \sum E_\gamma = 8\,MeV$$

Previously used in small scintillator detectors;
may be possible for large water detectors
with Gd compounds in solution

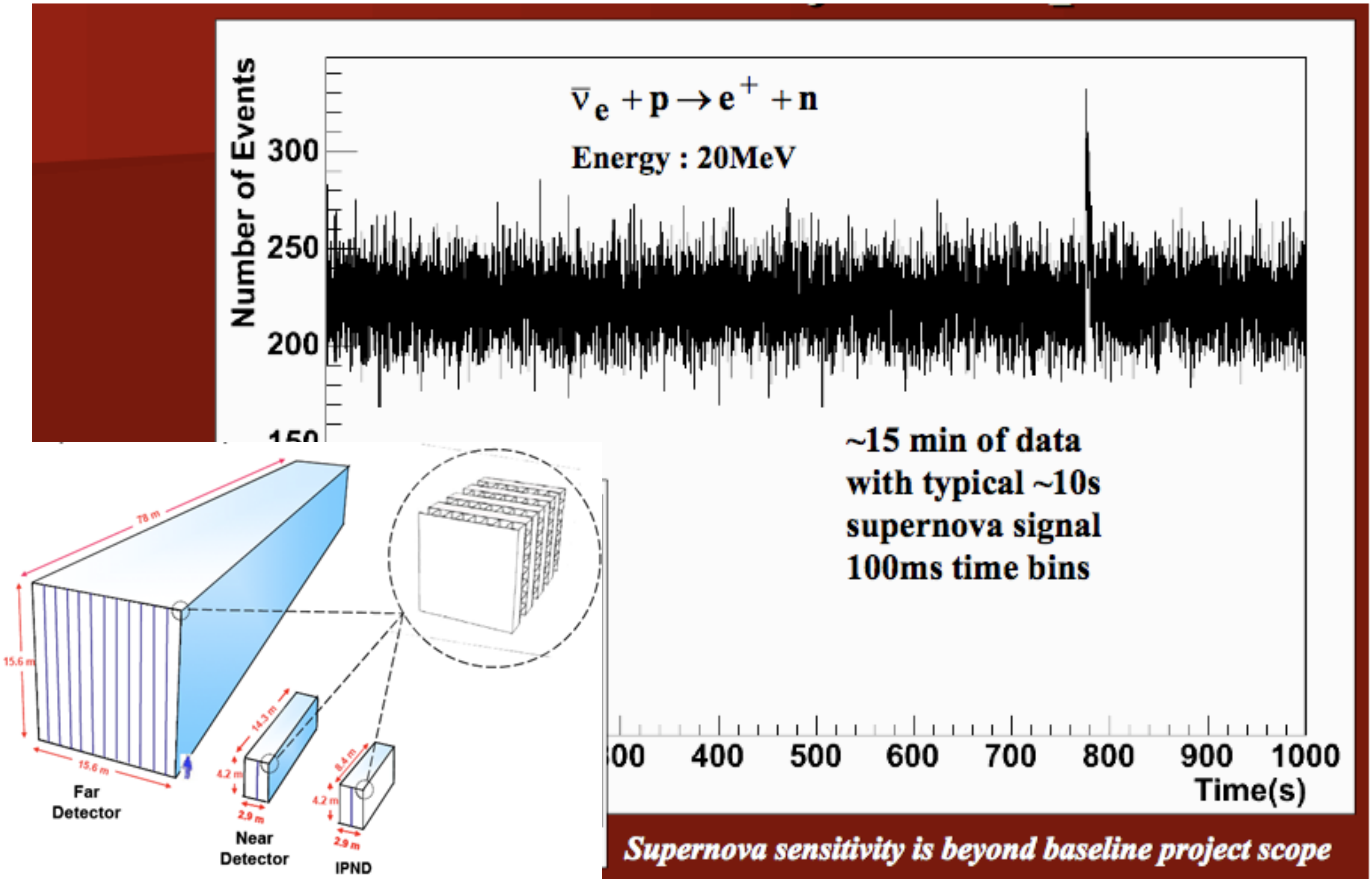


Beacom & Vagins, hep-ph/0309300
H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009), arXiv:0811.0735

About 4 MeV visible energy per capture;
~67% efficiency in SK
➔ *need good photocoverage*

NOνA: long baseline oscillation experiment (Ash River, MN)
15 kton scintillator, near surface

K. Arms, CIPANP '09



Although on the surface, reactor experiments w/ Gd-doped scintillator will record events!

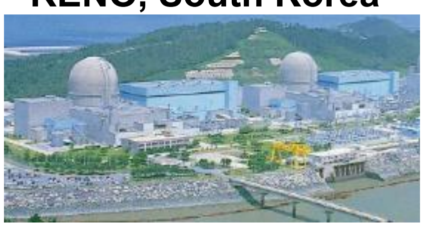
Detector	Type	Location	Mass (ton)	Events @ 10 kpc*
Double Chooz	Scintillator	France	20	**7**
RENO	Scintillator	South Korea	30	**11**
Daya Bay	Scintillator	China	160	**58**

* plus coherent ν-p scatters?

Although signal numbers are small, for low bg rates and good tagging, there will be good S/B

Also: coincidence between multiple detectors will help for a SN trigger

RENO, South Korea



Double CHOOZ, France

Daya Bay, China

Low energy neutrino interactions in argon

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Insufficient info in literature; ignoring for now

Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

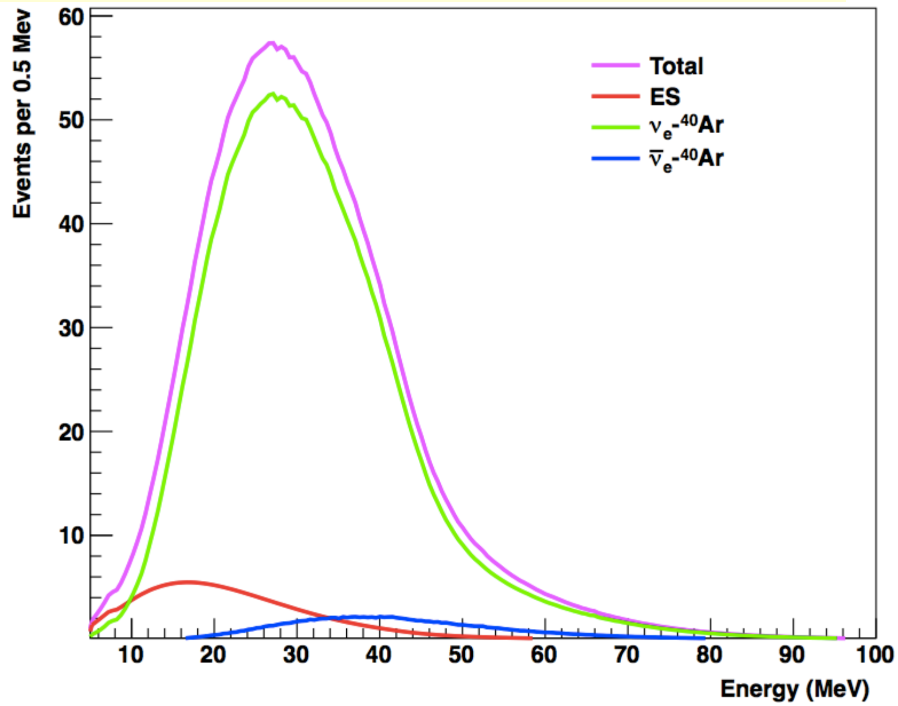
Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

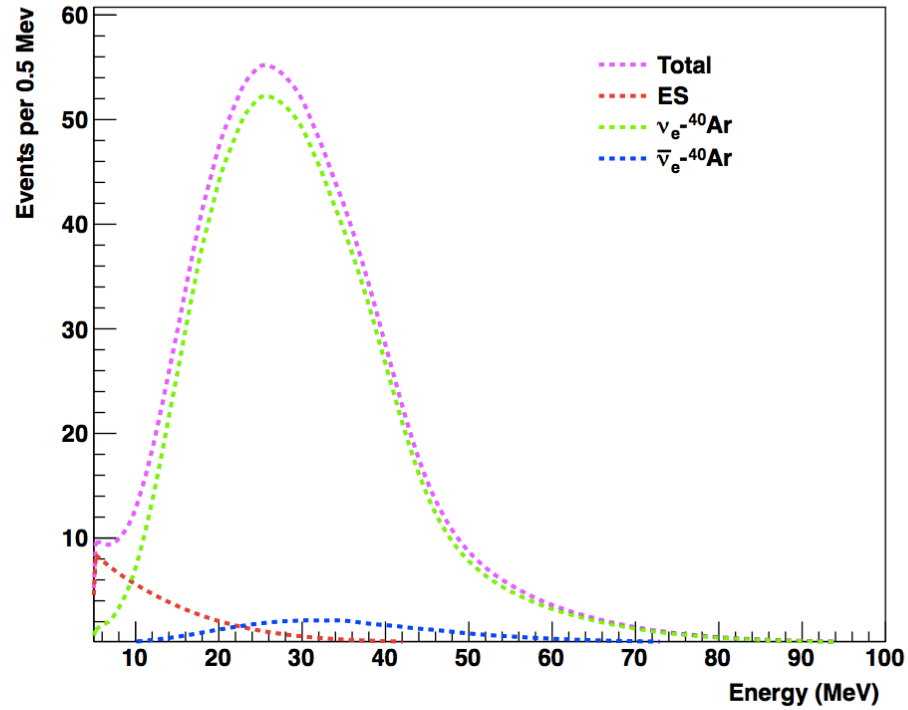
Supernova signal in LAr

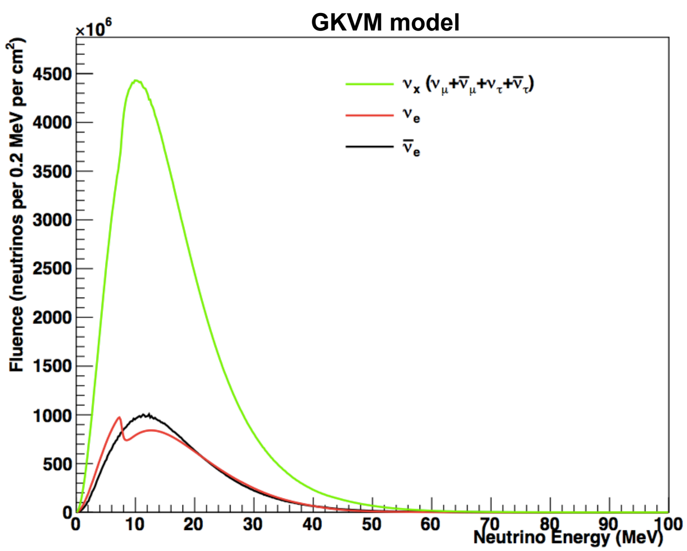
SN @ 10 kpc

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy





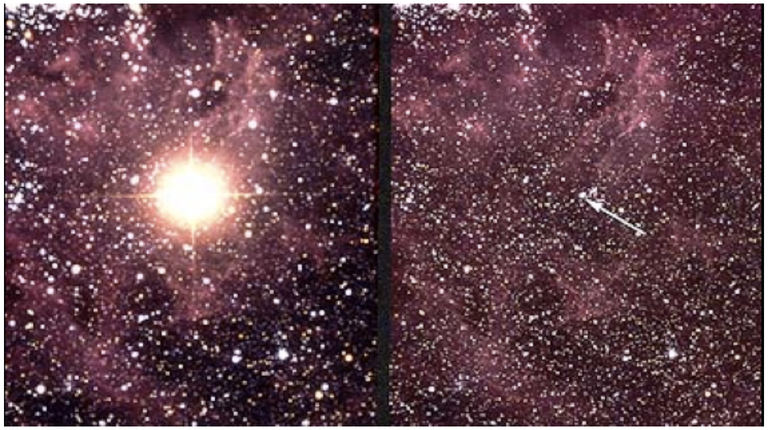
Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

Dominated by ν_e

An **EARLY ALERT** for astronomers

~hours of warning,

dependent on stellar envelope



Observations of light curve turn-on very rare for extragalactic SNae

Early light actually probably not that helpful for SN explosion theory (ν's are)

BUT:
- environment near progenitor probed by initial stages
- UV/ soft x-ray flash at shock breakout predicted

$\Rightarrow$ info about progenitor from spectroscopy

$\Rightarrow$ mass density profile for ν oscillation understanding

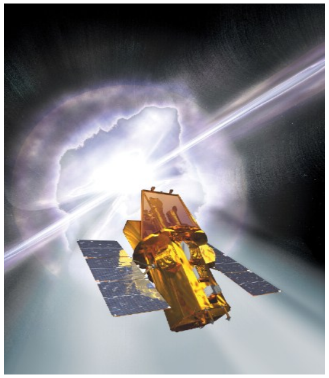
Plus: possible unknown early effects!

Any information saved, in any channel, may be valuable

- all em wavelengths
- neutrinos (low and high energy)
- gravitational waves
- ...

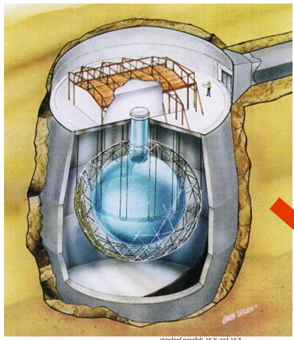
Combining information with other detectors sensitive to SNae is important! (alert & later)

gravitational waves



multiwavelength astronomy

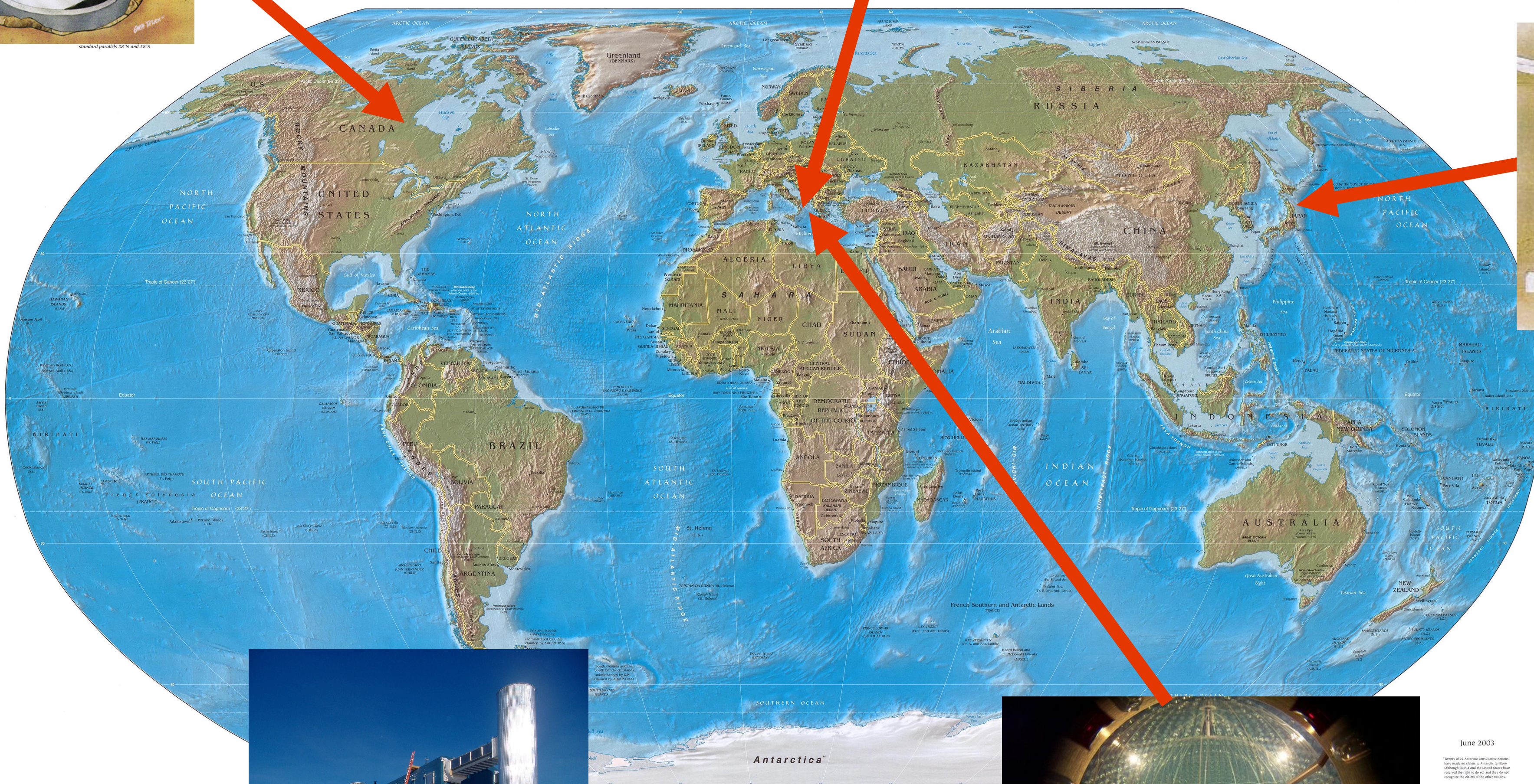
SNEWS: SuperNova Early Warning System

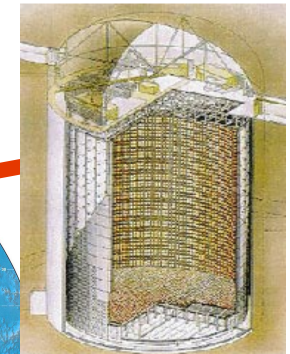


SNO
(until 2006)

LVD

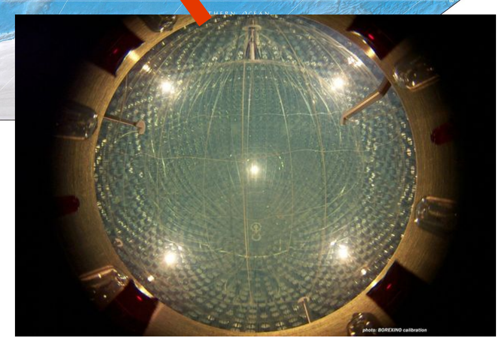
snews.bnl.gov





Super-K

IceCube

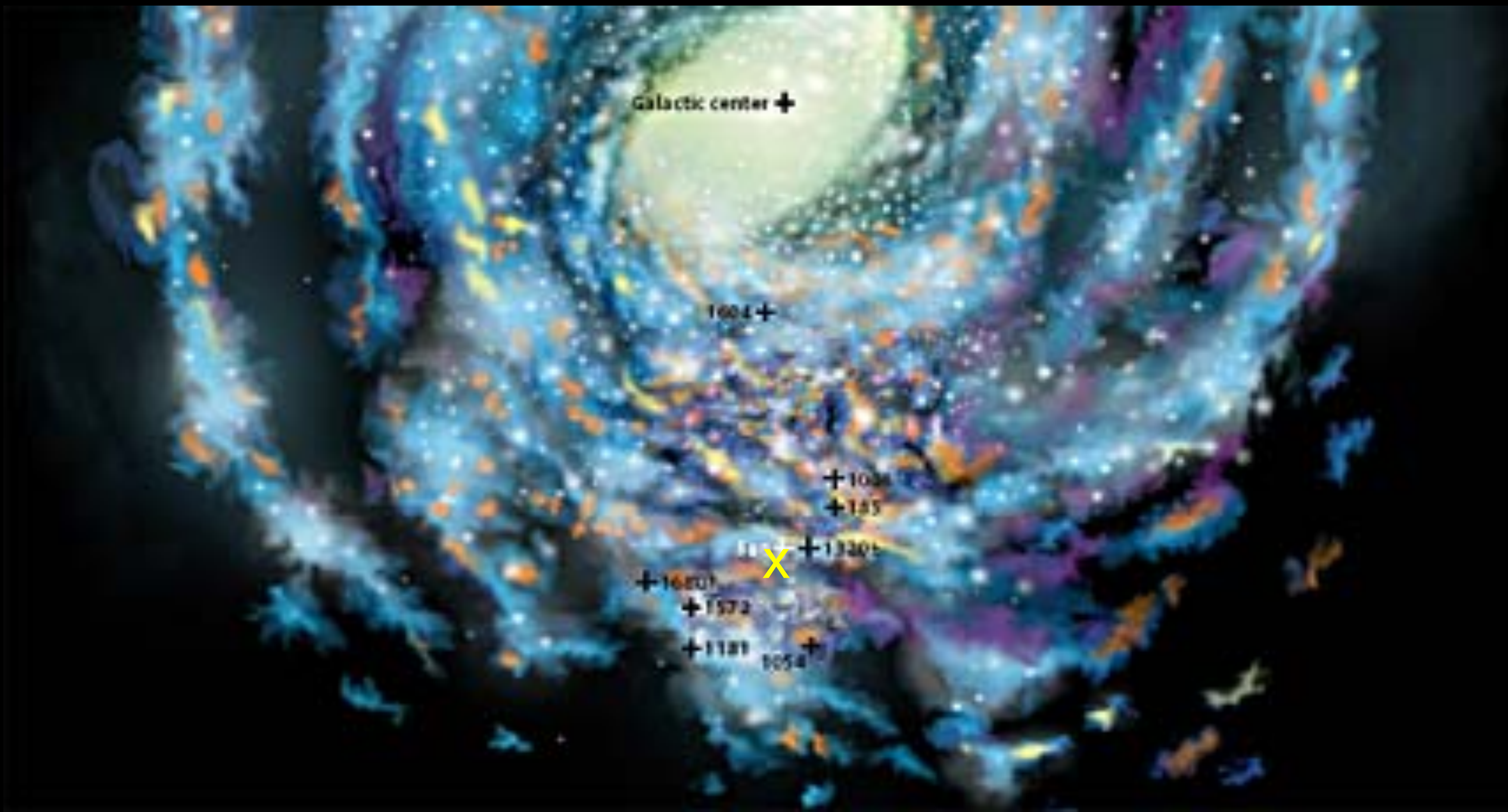


Borexino

Possibly 1/6 will stand out obviously...

Historical Supernovae:

(Sky&Telescope)

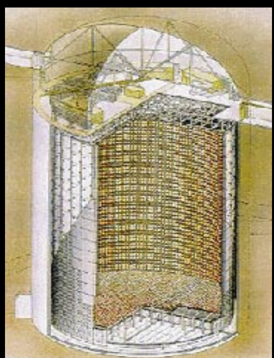


Also, fireworks may be intrinsically dim

SNEWS: SuperNova Early Warning System

- Neutrinos (and GW) precede em radiation by hours or even days
- For promptness, require *coincidence* to suppress false alerts

snews.bnl.gov

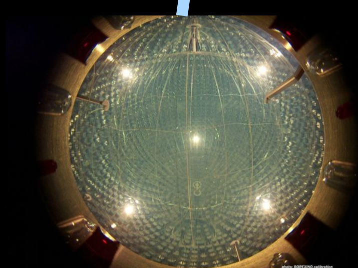


experiment
UT time
significance

Coincidence Server at BNL

10 second coincidence by UT time stamp

alert to astronomers



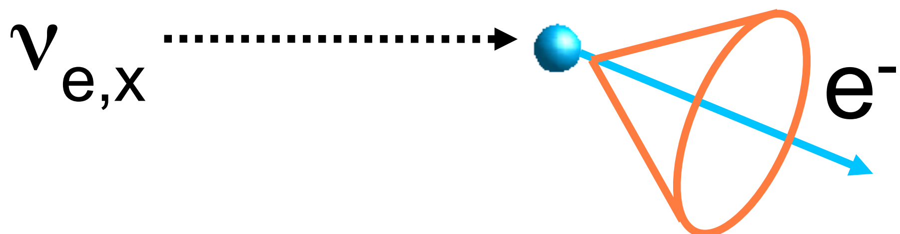
- Running smoothly for more than 10 years, automated since 2005
- Amateur astronomer connection

POINTING to the supernova with future detectors

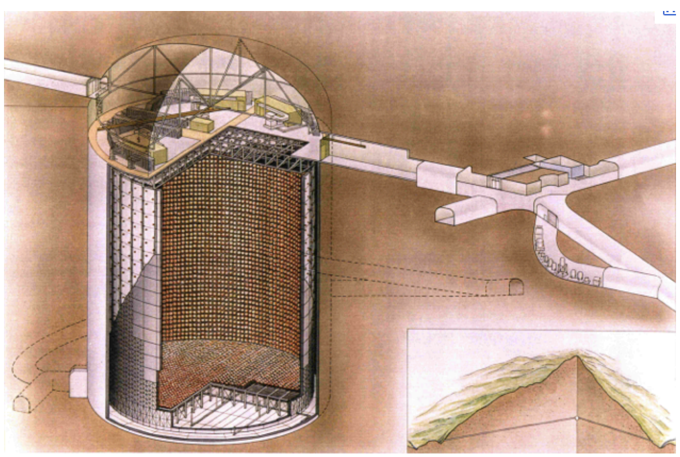
(should be prompt if possible)

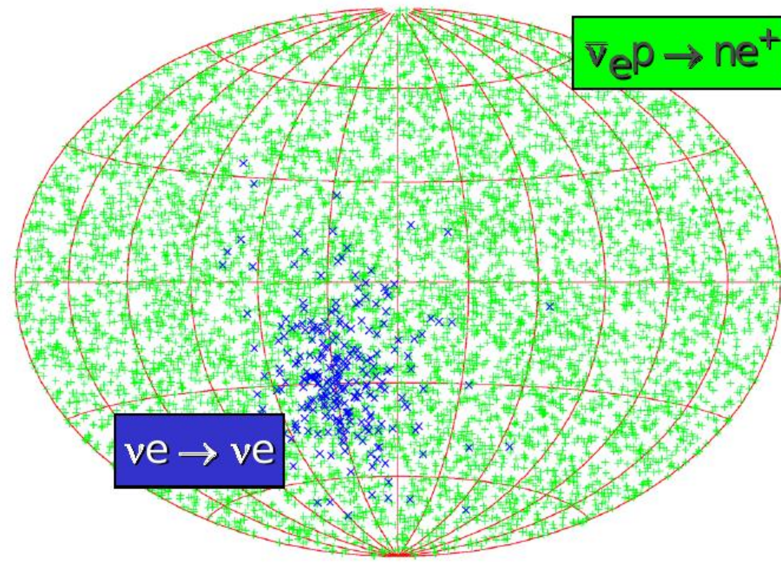
Elastic scattering off electrons is the best bet

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$



In water Cherenkov few % of total rate





G. Raffelt

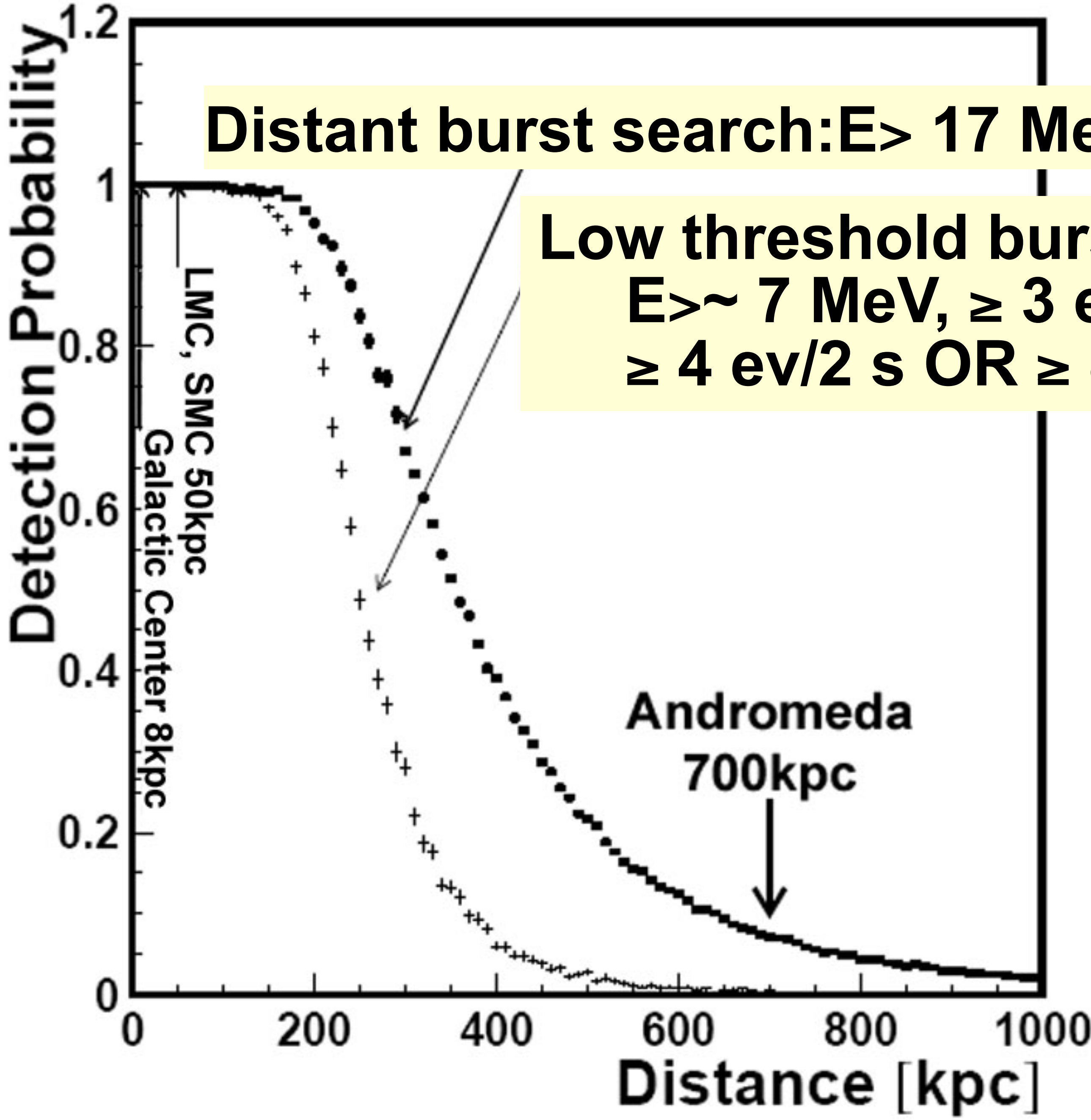
Super-K: ~8° pointing

Other possibilities:
- time triangulation
- matter oscillation pattern
- inv. βdk e^+n separation
- ~TeV neutrinos (delayed)

KS, A. Burgmeier, R. Wendell
arXiv: 0910.3174

Tomas et al.,hep-ph/0307050

How far can we look out? SK has farthest reach now



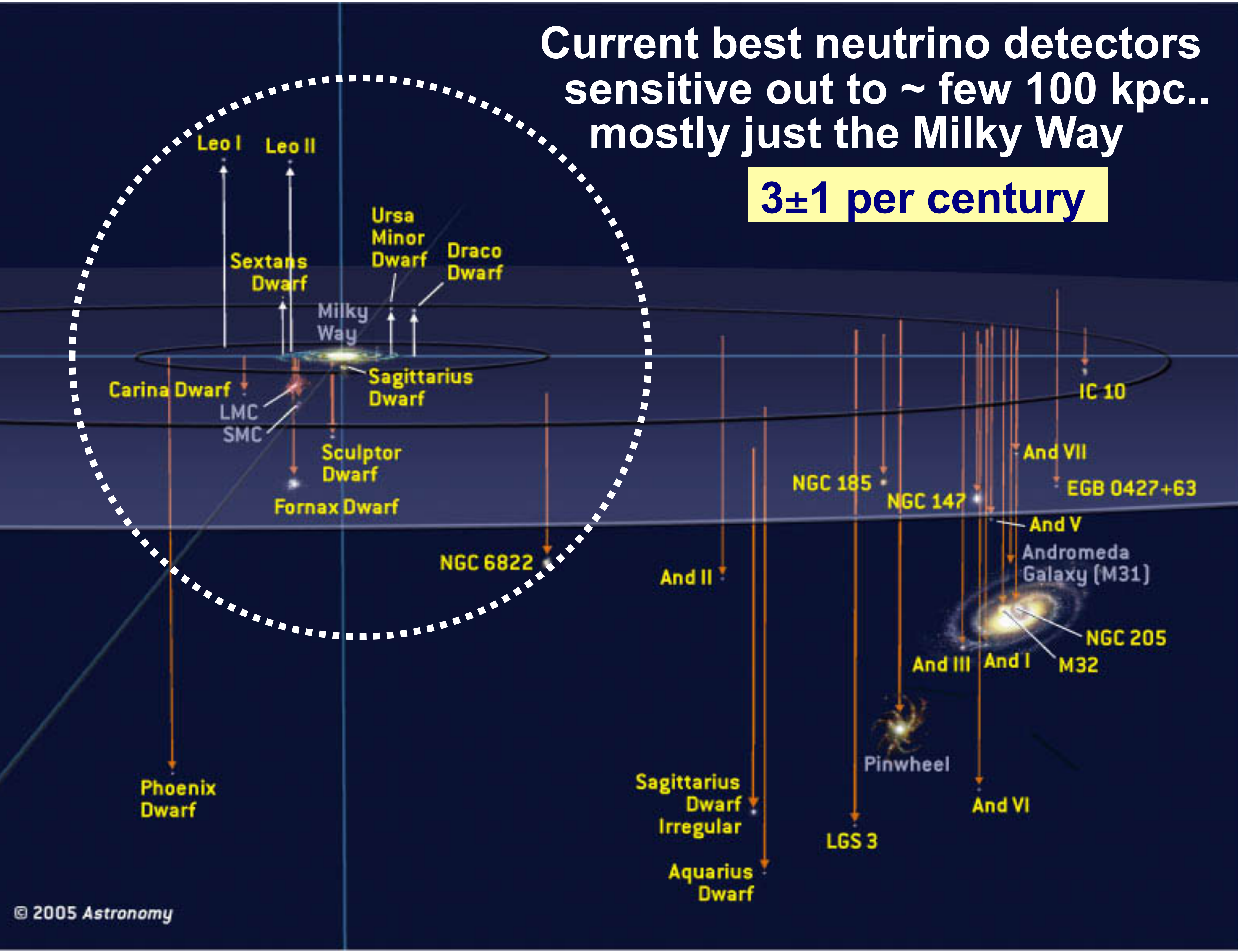
Distant burst search: E> 17 MeV, ≥ 2 ev/20 s

Low threshold burst search:
E>~ 7 MeV, ≥ 3 ev/0.5 s OR
≥ 4 ev/2 s OR ≥ 8 ev/10 s

Ikeda et al., arXiv:0706.2283

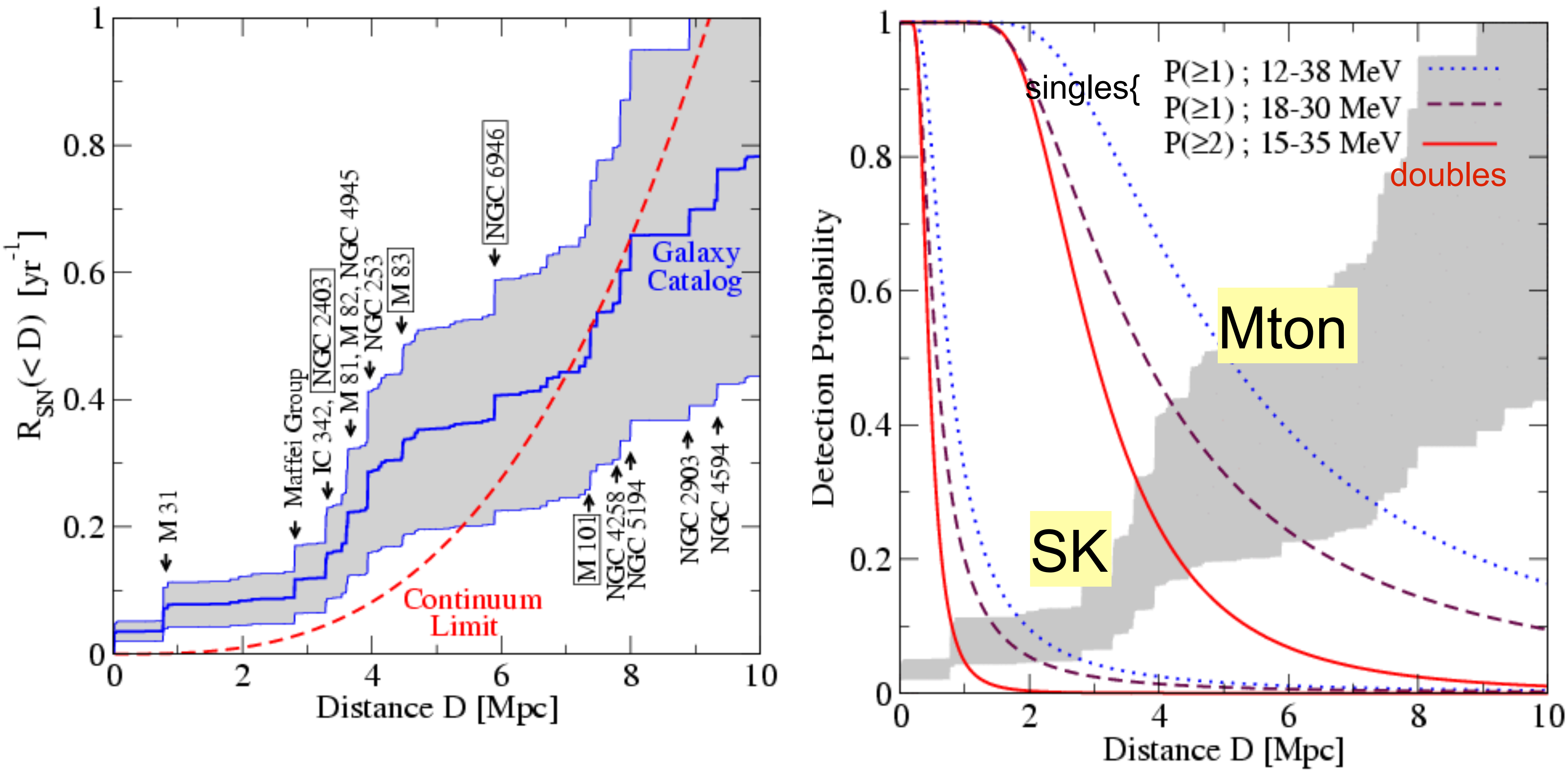
Current best neutrino detectors sensitive out to ~ few 100 kpc.. mostly just the Milky Way

3±1 per century



Looking beyond: number of sources α D^3

S. Ando et al., astro-ph/0503321



With Mton scale detector, probability of detecting 1-2 events reasonably close to ~1 at distances where rate is <~1/year

Tagging signal over background becomes the issue
⇒ require double ν's or grav wave/optical coincidence

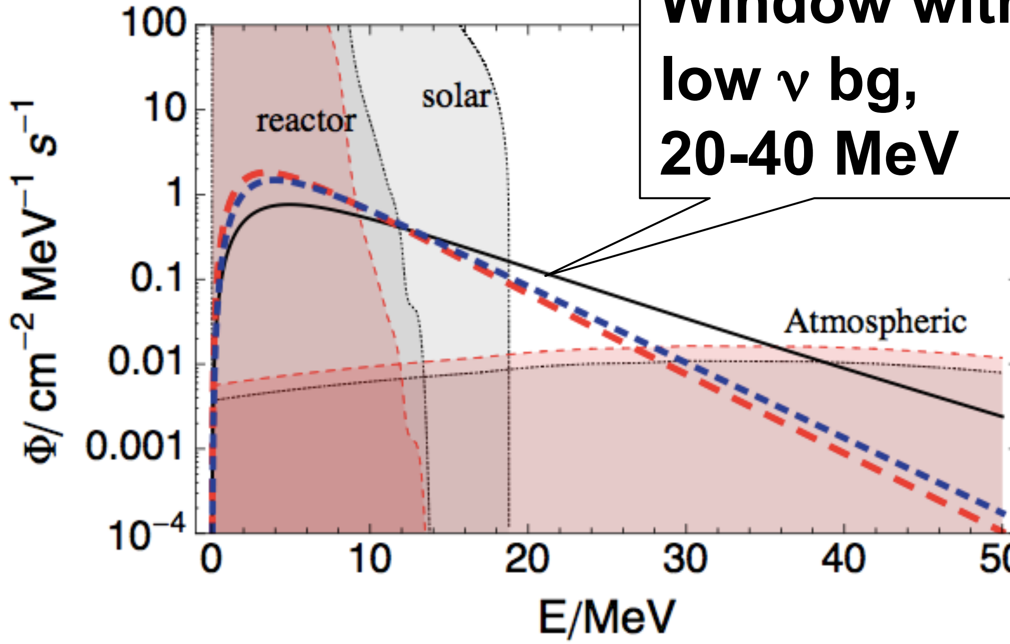
Table 2 Summary of neutrino detectors with supernova sensitivity[a]

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980–present
LVD	C_nH_{2n}	1	Italy	300	1992–present
Super-Kamiokande	H_2O	32	Japan	7,000	1996–present
KamLAND	C_nH_{2n}	1	Japan	300	2002–present
MiniBooNE[b]	C_nH_{2n}	0.7	USA	200	2002–present
Borexino	C_nH_{2n}	0.3	Italy	100	2005–present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007–present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE[b]	Ar	0.17	USA	17	Near future
NOνA[b]	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE with water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

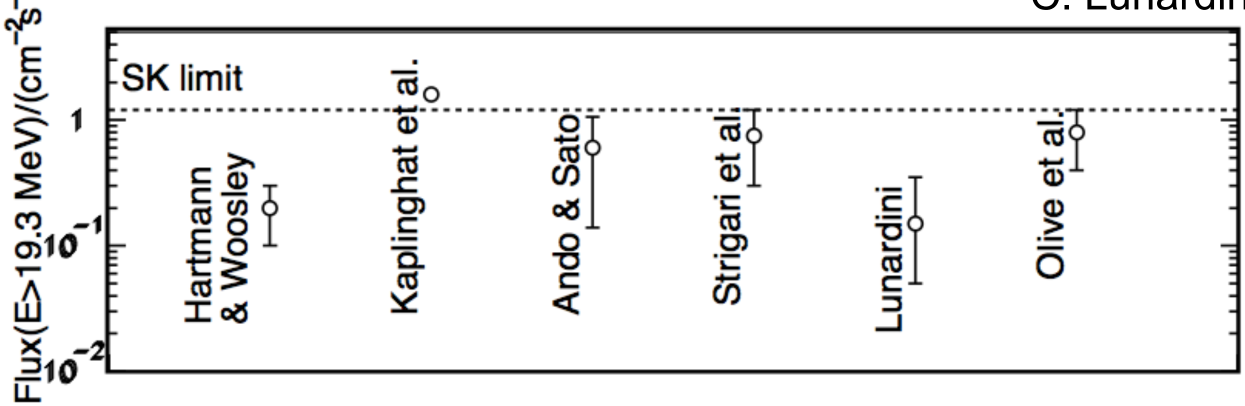
And going even farther out: we are awash in a sea of *'relic'* or diffuse SN ν's (DSNB), from ancient SNae

Learn about average supernova properties over cosmic history

Difficulty is tagging for decent signal/bg (no burst, 2 ν coincidences optical SNae...)

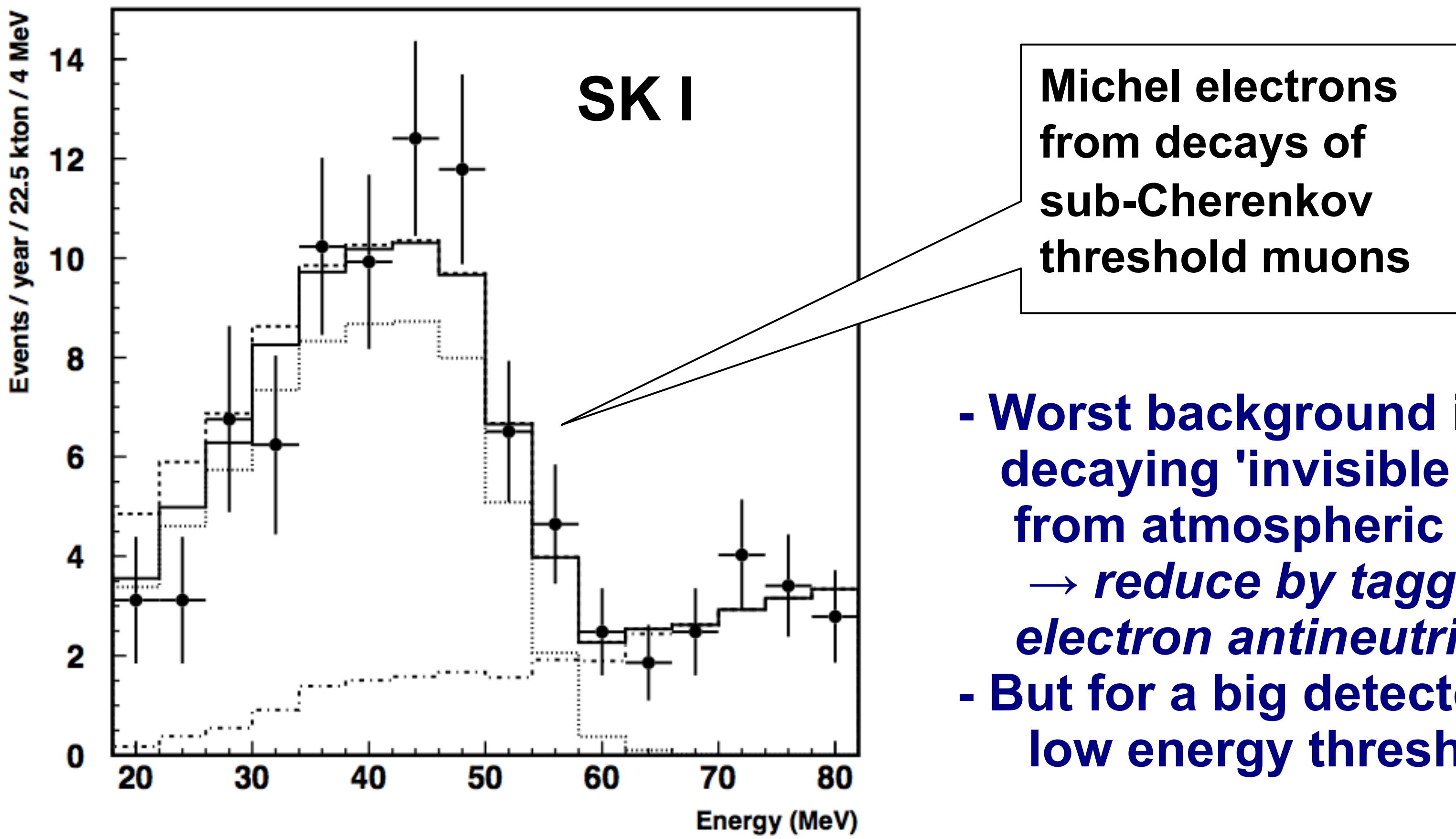


C. Lunardini



~few events per year in SK

In water: $\bar{\nu}_e + p \rightarrow e^+ + n$



- **Worst background is from decaying 'invisible muons' from atmospheric neutrinos**
  → *reduce by tagging electron antineutrinos with Gd*
- **But for a big detector requires low energy threshold ($)**

LAr? **Electron flavor, but low rate... bg unknown**

Scintillator? **Good IBD tagging, but NC bg**

DSNB	Galactic SN
	~300 events/kt/30 year
~0.1 event/kt/year	~10 events/kt/yr
more background	less background
low rate of return, but a sure thing	risky in the short term, but you win in the very long term

bonds vs stocks...

(Of course if you build a big detector and run it a long time, you may get both! Diversify!)

(But we must remember that no experiment is 'too big to fail'...)

Tool for evaluating neutrino event rates

To evaluate sensitivity to different features of flux/physics, we need to fold

$$\text{flux} \otimes \text{xscn} \otimes \text{detector response}$$

Software package to make use of the GLoBES front-end rate engine (*not* the oscillation sensitivity part)

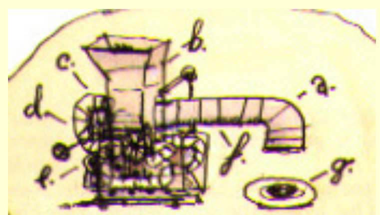
flux differential spectra w/physics

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

SNOw GLoBES



interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

what we're after

SNOwGLoBES package contents

- driving script
- data files:
    - cross-section files for O, Ar, C, Pb (+...)
    - smearing and efficiency files for several detector configurations (100kt, LAr, scint, HALO)
    - example flux file(s)
- example plotting scripts
- documentation w/refs

A. Beck, F. Beroz, R. Carr, KS, W. Johnson, A. Moss, D. Reitzner, D. Webber, R. Wendell
A. Dighe, H. Duan, A. Friedland, J. Kneller

- Smearing and efficiency files provided are based on:
    - published information (resolutions etc.), reasonable assumptions, simulation output where available
- Users (typically) would provide their own fluxes
- Users could use the packaged detector smearing datafiles, or provide their own

`http://www.phy.duke.edu/~schol/snowglobes`

- Test version available

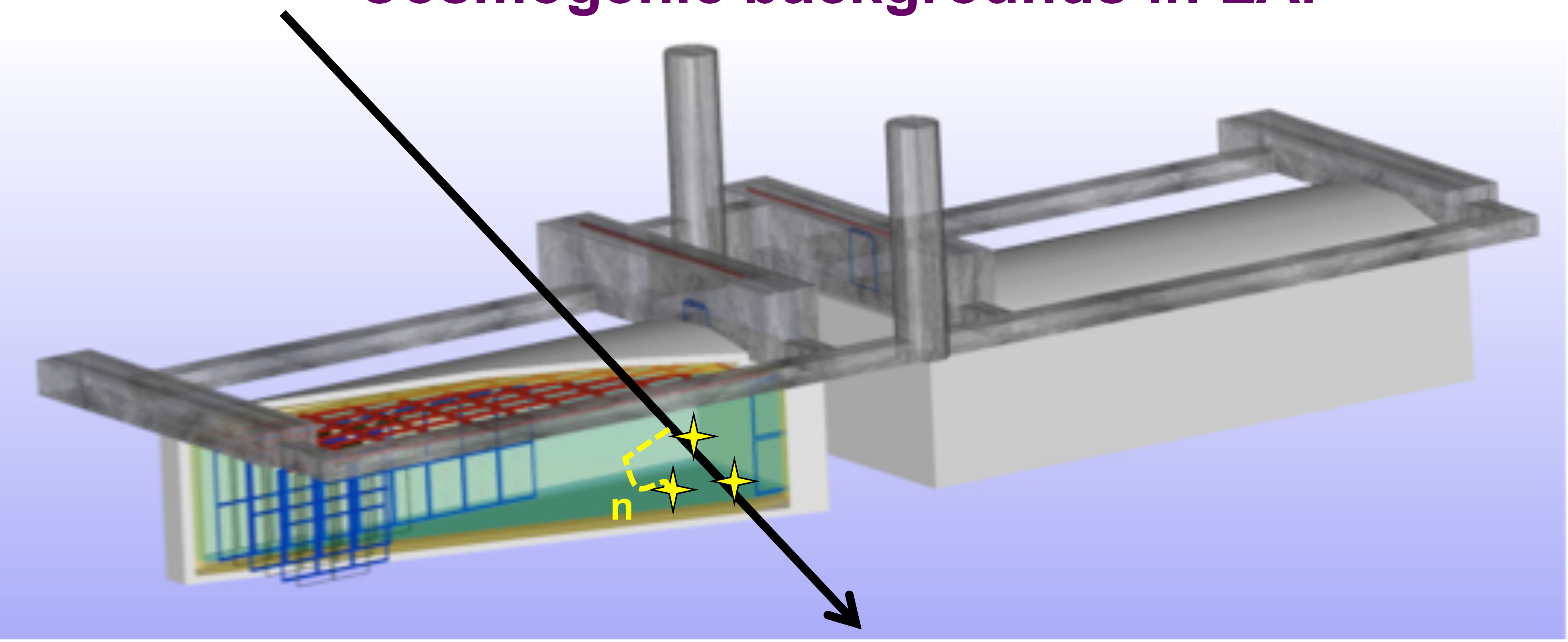
Recent work by Barker, Mei & Zhang, arXiv:1202.5000

Muon-Induced Background Study for an Argon-Based Long Baseline Neutrino Experiment

D. Barker,[1] D.-M. Mei,[1,*] and C. Zhang[1,2]

- Geant4 study w/ 20 kton LAr detector @ 800 ft & 4850 ft
- Muon & muon-induced neutron spectra from Mei & Hime 2006
- Backgrounds considered:
  - muon-induced fast neutrons
  - ^{40}Cl from muon capture, neutrons, secondaries
  - radioactive isotopes from spallation & hadronic interactions

Cosmogenic backgrounds in LAr

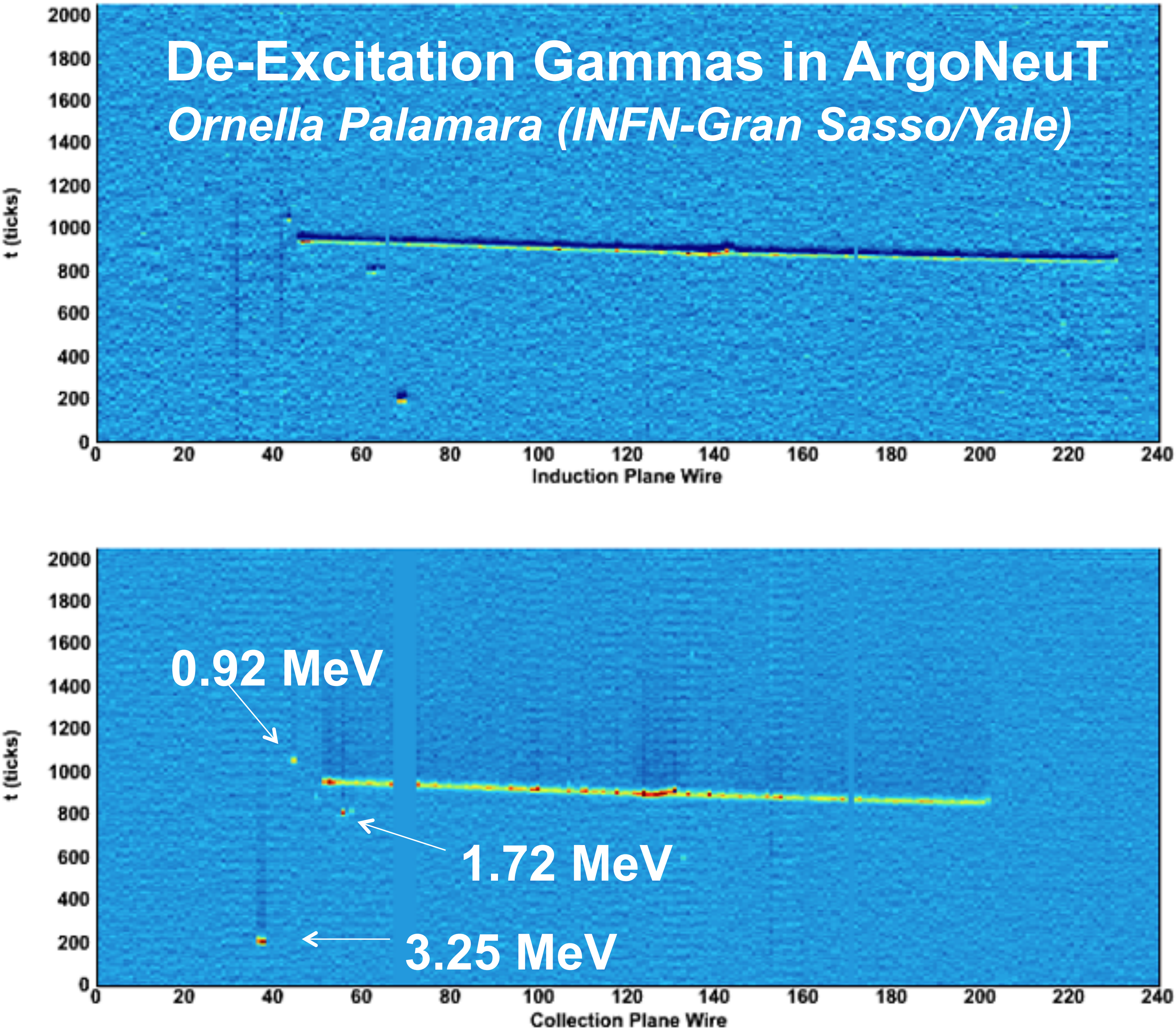


- cosmic rays can rip apart nuclei, leaving radioactive products that can decay on ms-hour (day, year..) timescales
- neutrons, muon capture can also be problematic
- fairly well understood in water & scintillator, but few studies in argon

- in principle can be associated with parent muons (need photons...)
- in principle mitigation strategies exist (e.g. γ tagging) but efficiency currently unknown

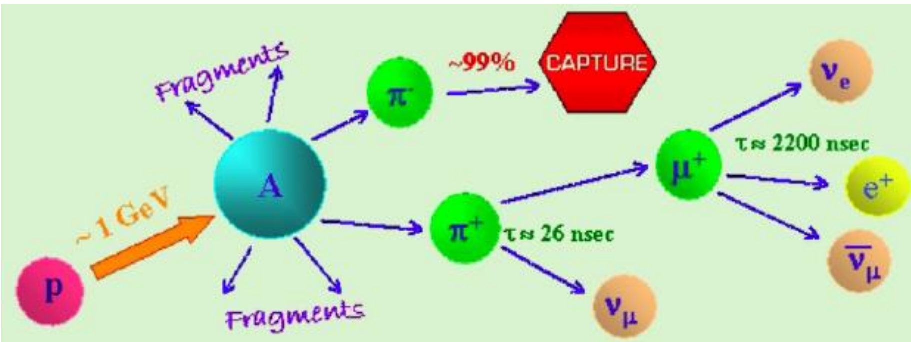
De-Excitation Gammas in ArgoNeuT

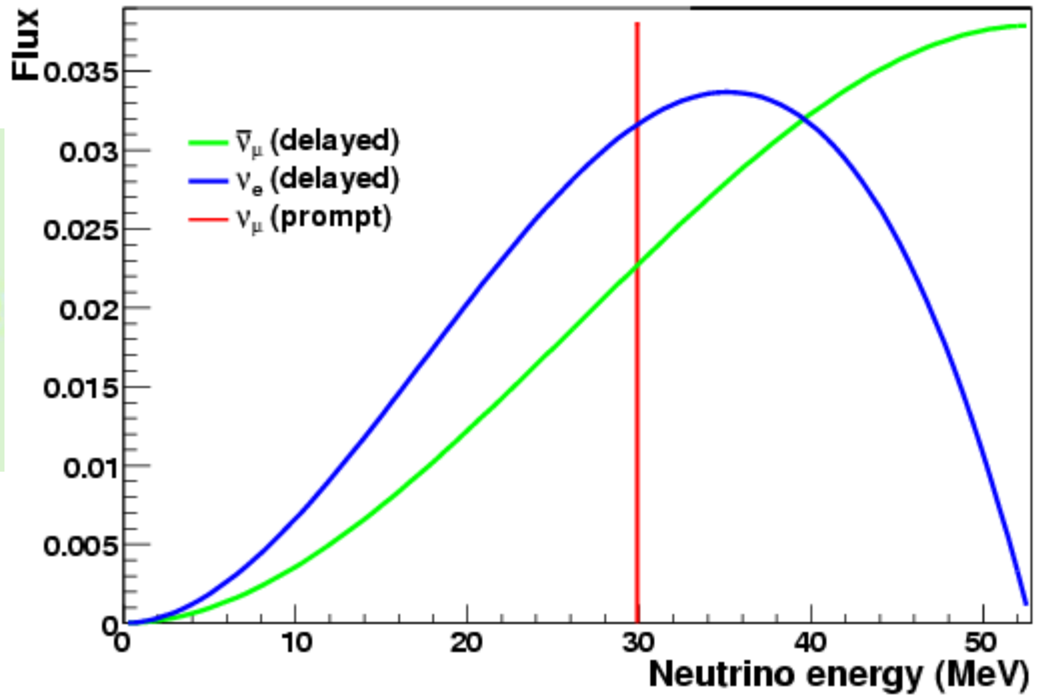
Ornella Palamara (INFN-Gran Sasso/Yale)



Expected DAR neutrino spectrum

F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

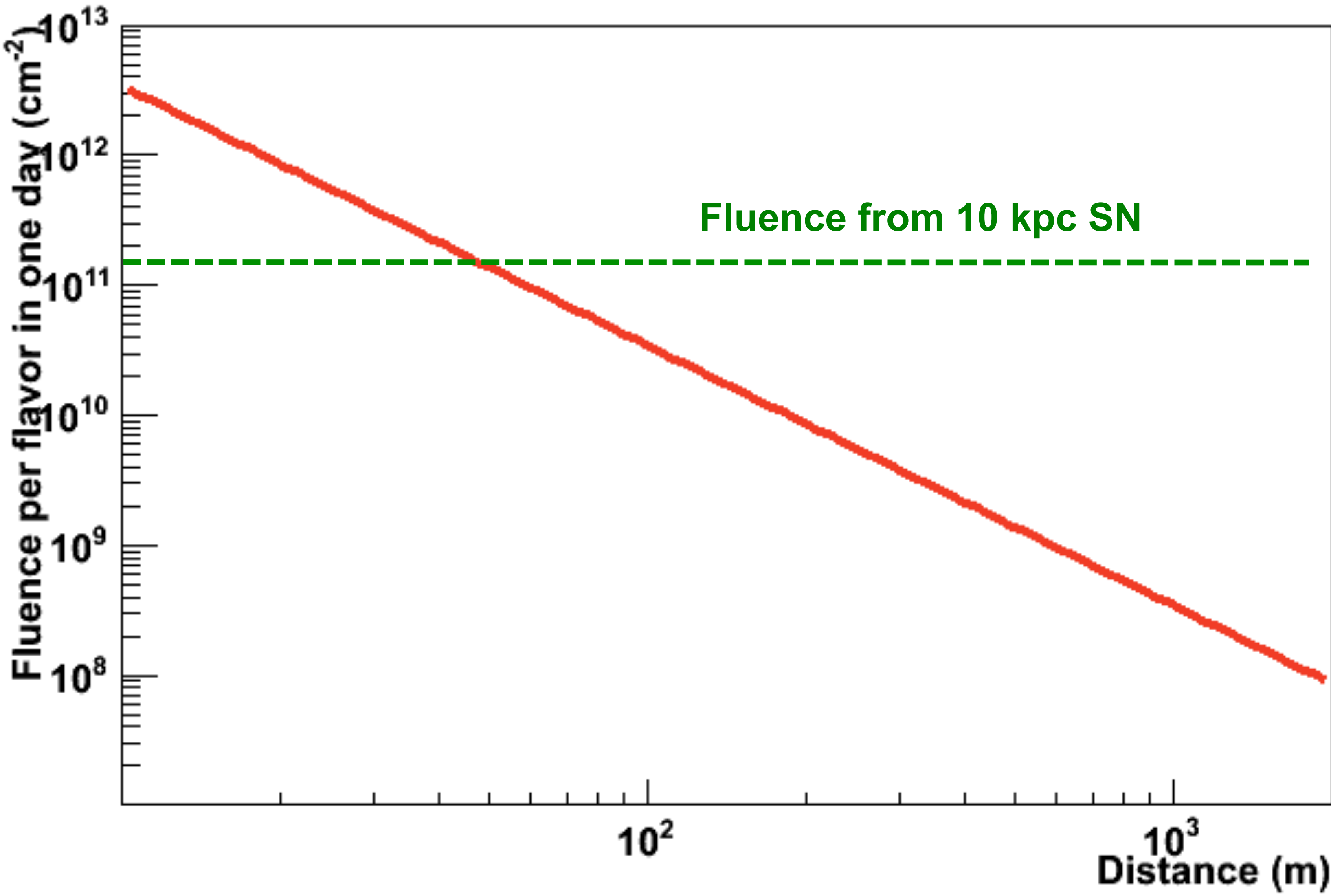
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

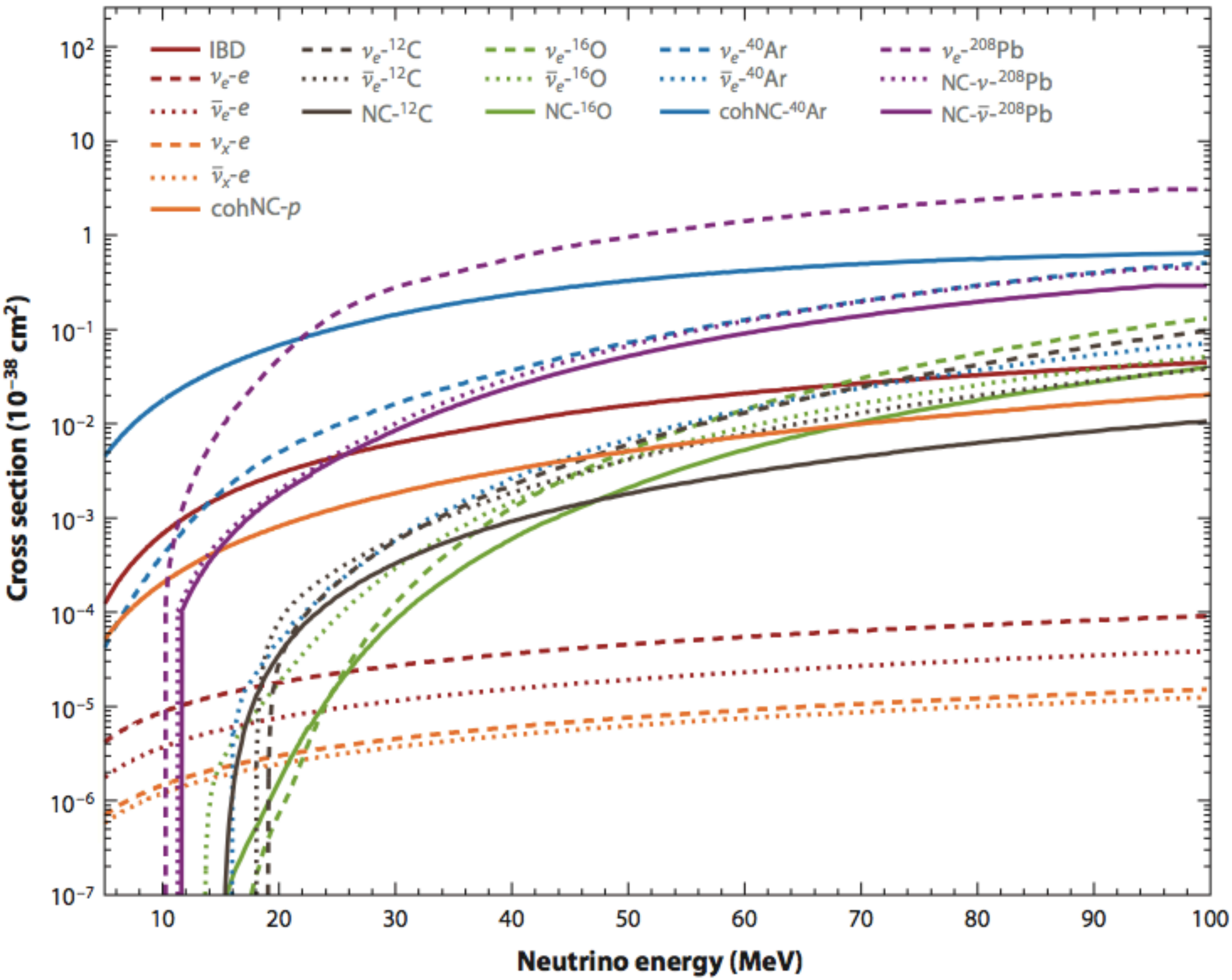
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!



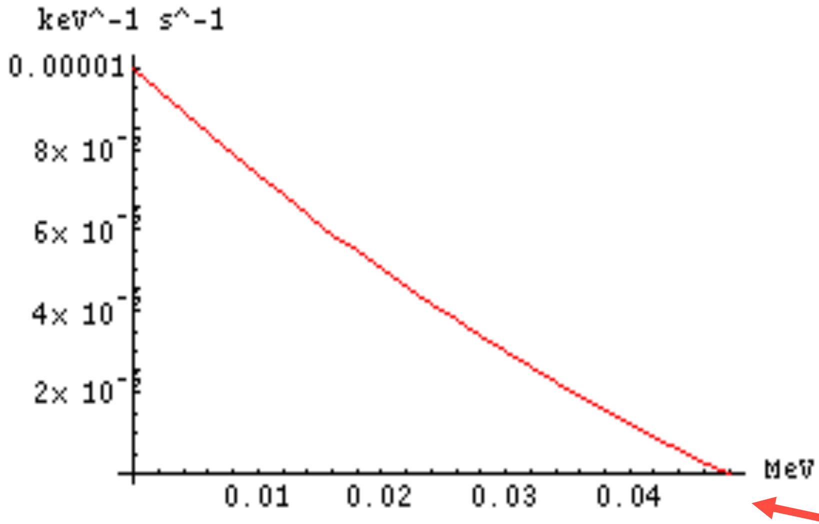


IBD
ν_e-e
$\bar{\nu}_e$-e
ν_x-e
$\bar{\nu}_x$-e
cohNC-p
ν_e-^{12}C
$\bar{\nu}_e$-^{12}C
NC-^{12}C
ν_e-^{16}O
$\bar{\nu}_e$-^{16}O
NC-^{16}O
ν_e-^{40}Ar
$\bar{\nu}_e$-^{40}Ar
cohNC-^{40}Ar
ν_e-^{208}Pb
NC-ν-^{208}Pb
NC-$\bar{\nu}$-^{208}Pb
Cross section (10^{-38} cm^2)
Neutrino energy (MeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10
20
30
40
50
60
70
80
90
100

But this coherent ν A elastic scattering has never been observed...

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



Max recoil energy is $2E_\gamma^2/M$ (48 keV for Ar)

Recoil energies are tiny!

Most neutrino detectors (water, gas, scintillator) have thresholds of at least ~MeV: so these interactions are hard to see

Why try to measure this?

- It's never been done!

- Important in supernova processes
- Important for supernova ν detection

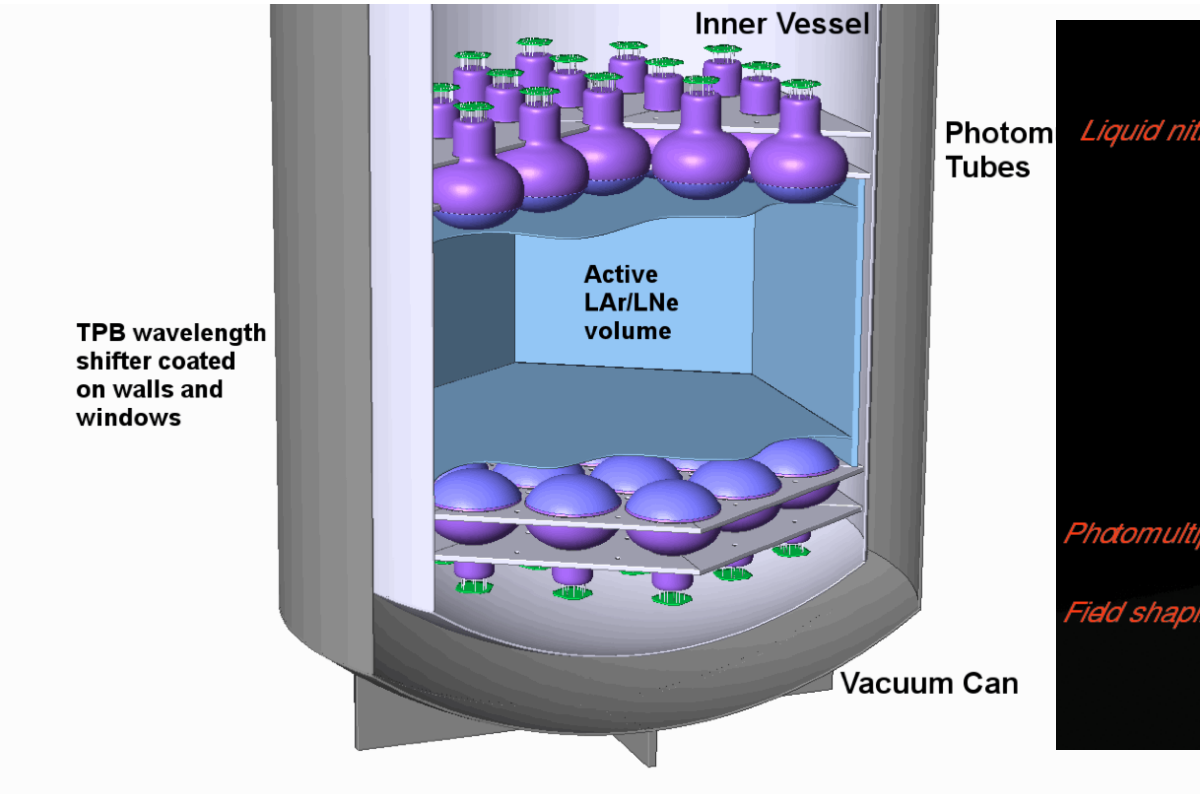
- Deviations from expected x-scn may indicate non-SM processes

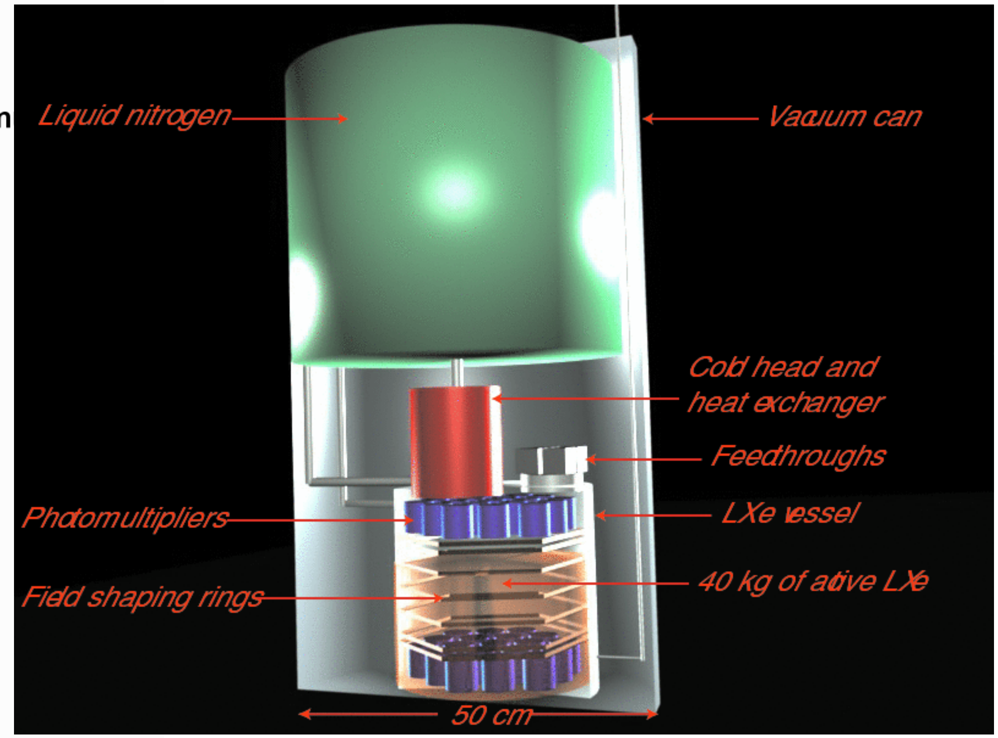
???

- Possibly even applications..

e.g. Barbeau et al., IEEE Trans. Nucl. Sci. 50: 1285 (2003)
C. Hagmann & A. Bernstein, IEEE Trans. Nucl. Sci 51:2151 (2004)

Detector possibilities: various DM-style strategies



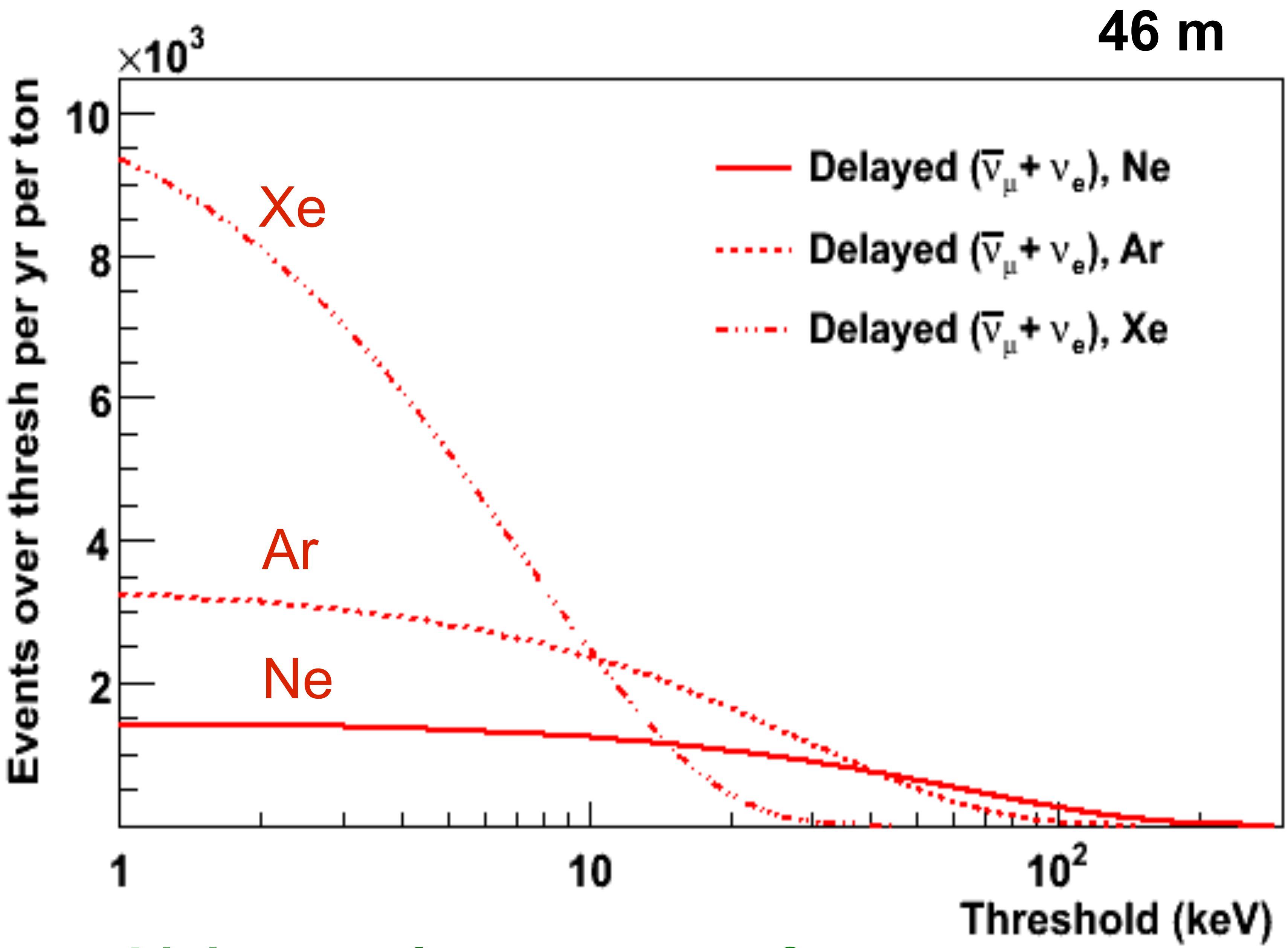


Single-phase Ar/Ne (CLEAR)

arXiv:0910.1989

Xe TPC

Integrated SNS yield for various targets



Lighter nucleus ⇒ expect fewer interactions, but more at higher energy

What physics could be learned from measuring this?

KS, Phys. Rev D 73 (2006) 033005

Basically, any deviation from SM cross-section is interesting...

- **Weak mixing angle**
- **Non Standard Interactions (NSI) of neutrinos**
- **Neutrino magnetic moment (hard)**
- **Nuclear physics**

SNS Flux for SNOwGLoBES

Normalized to 10^7 per cm^2 per s per flavor at 20 m